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Design of a Tri-Adjustable Automated Heavy-Duty Handling System Based on Industry 4.0 Principles

A DISSERTATION

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ABSTRACT

Materials Handling (MH) is one of the most essential aspects within manufacturing processes and/or industries. MH equipment are mechanical equipment used for the movement, storage, control and protection of materials, goods, and products throughout the process of manufacturing, distribution, consumption, and disposal. Transportation equipment used in manufacturing industries varies from pallet jack to forklift trucks and/or cranes. The size and type of a Material Handling System (MHS) and/or equipment influences the effectivity of the internal logistics within manufacturing industries. Therefore, it is very essential to choose a correct MHS for a correct manufacturing process which requires material handling to coFmplete its operation. Incorrect usage or selection of an MHS for an operational process may lead to down time, damage to facility, increase in operating costs and/or pose Occupational Health and Safety (OHS) risks to workers.

Over the years, many South African industries have been using Forklift trucks to move bigger loads from one point to another till today. The use of large forklift trucks within indoor manufacturing processes poses OHS risks to workers as its Internal Combustion Engine (ICE) produces fumes (Carbon Monoxide, CO) when in operation and exhaust fumes, (CO), are harmful to human's health. On this basis, a new system design is recommended to eliminate the use of MHS that relies on ICE power source to prevent OHS risks in indoor manufacturing industries. In this project, Autodesk Inventor Professional software was used for design development of technical drawings and simulation as well as validation of the new system's structure. Vehicle Dynamics' principles and equations are used to determine the overall Rolling Resistance, Tractive Effort of the new system, wheel torque, and the power required to drive the system under 20 – ton load capacity. The new system design has been developed to operate using a Hydraulic Power pack source, where it consists of four hydraulic wheel hubs for driving the system, four hydraulic cylinders for lifting & lowering, and a double rod end hydraulic cylinder for steering. Electro-Hydraulic circuit systems were developed and proposed using electronics and fluid mechanics phenomena. Again, principles, laws and equations of Strength of Materials has been carried out for validation of the material selection of the new design system's structure as well as verifying buckling, deflection & bending stresses, and moments.

Keywords: Material Handling System, Internal Combustion Engine, Occupational Health & Safety, Manufacturing, Hydraulics, Automation, Design, Industry 4.0, Tractive Effort, Finite Element Methods.

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GENERAL DEFINITIONS

Automation: the technique of making an apparatus, a process, or a system operate automatically.

Carbon Monoxide (CO): is a poisonous gas that has no smell or taste. Breathing it in can make you unwell, and it can kill if you are exposed to high levels.

Finite Element Analysis: is the simulation of a physical phenomenon using a numerical mathematic technique referred to as the Finite Element Method, or FEM.

Factor of Safety expresses how much stronger a system is than it needs to be for an intended load.

Hydraulic System: uses force that is applied at one point and is transmitted to another point using an incompressible fluid.

Industry 4.0: is the digital transformation of manufacturing/production and related industries and value creation processes.

Internal Combustion Engine (ICE): an engine which generates motive power by the burning of petrol, oil, or other fuel with air inside the engine, the hot gases produced being used to drive a piston or do other work as they expand.

Material Handling (MH): is the movement, protection, storage and control of materials and products throughout manufacturing, warehousing, distribution, consumption, and disposal.

Material Handling System (MHS): is mechanical equipment used for the movement, storage, control and protection of materials, goods, and products throughout the process of manufacturing, distribution, consumption, and disposal.

Occupational Health & Safety act 85 of 1993: is the law that seeks to protect the well-being of workers. The OHS Act is enforced by the Department of Labour.

Spreader Beam: are designed to direct load to top rigging and hooks, requires a greater amount of headroom than a lifting beam.

Tractive Effort (TE): the force at the outer edges of the driving wheels of moving vehicles. In other words, it is the sum of the tractive force and rolling effort/resistance on the road surface.

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ABBREVIATIONS AND ACRONYMS

BRC:	Barloworld Remanufacturing Center
CO:	Carbon Monoxide
FEA:	Finite Element Analysis
FOS:	Factor of Safety
ICE:	Internal Combustion Engine
ISO:	International Standards Organization
MH:	Material Handling
MHS:	Material Handling System
OHC:	Over Head Crane
OHS:	Occupational Health & Safety
PDS:	Product Design Specifications
RR:	Rolling Resistance
SABS:	South African Bureau of Standards
TE:	Tractive Effort

SYMBOLS

Symbol	Description		Symbol	Description
F_a	Acceleration Force (N)		**EI**	Moment Relation
g	Acceleration due to gravity, (m/s^2)		A_a	Piston Area (m^2)
ω	Angular Velocity (rads/s)		**P**	Power (W)
BM	Bending Moment (N.m)		**P**	Pressure Fluid (kPa)
b	Breadth (m)		**R**	Resistance (ohms)
I	Current (A)		**RR**	Rolling resistance (N)
S	Cylinder Stroke (m)		**N**	Rotational Speed (rpm)
μ	Coefficient of Friction		v	Shear Force (N)
δ	Deflection (mm)		τ	Shear Stress (Pa)
$\bar{y}$	Distance at Neutral axis (mm)		**U**	Strain Energy
ρ:	Density of Material (kg/m^3)		**t**	Time (s)
n	Factor of safety		**T**	Torque (N.m)
Q	Flow Rate (m^3/min)		**TE**	Tractive Effort (N)
H	Height (m)		**d**	Tube diameter (mm)
γ	Hydraulic Efficiency		**t**	Thickness of Material (mm)
L	Length (m)		**v**	Velocity (m/s)
a	Linear Acceleration (m/s^2)		V	Volume (m^3)
V	Linear Velocity (m/s)		**V**	Volts (V)
m	Mass (kg)		W	Weight (N)
M	Moment (N.m)		**W**	Width (m)
I	Moment of Inertia (m^4)		**E**	Young's Modulus (GPa)

CHAPTER ONE

INTRODUCTION AND SCOPE OF WORK

1. Project Background

Material Handling (MH) is one of the most essential aspects within manufacturing processes/industries. Transportation equipment used in most South African manufacturing industries varies from pallet jack to forklift trucks and/or cranes. Material Handling equipment are mechanical equipment used for the movement, storage, control and protection of materials, goods, and products throughout the process of manufacturing, distribution, consumption, and disposal [1,2].

A common approach to the design of Material Handling systems (MHSs) is to consider Material Handling as a cost to be minimized. This approach may be the most appropriate in many situations because, while Material Handling can add real value to a product, it is usually difficult to identify and quantify the benefits associated with Material Handling Systems; it is much easier to identify and quantify the costs of Material Handling (e.g., the cost of Material Handling equipment, the cost of indirect Material Handling labour, etc.). Once the design of a production process (exclusive of Material Handling considerations) is completed, alternate Material Handling System designs are generated, each of which satisfies the Material Handling requirements of the production process. The least cost Material Handling System design is then selected [3,5].

The suitability of the use of Material Handling System cost as the sole criterion to select a Material Handling System design depends on the degree to which the other aspects of the production process can be changed. If a completely new facility and production process is being designed, then the total cost of production is the most appropriate criterion to use in selecting a Material Handling System - the lowest cost Material Handling System may not result in the lowest total cost of production. If it is too costly to even consider changing the basic layout of a facility and the production process, then Material Handling System cost is the only criterion that need be considered. In practice, it is difficult to consider all the components of total production cost simultaneously, even if a new facility and production process is being designed. Aspects of the design that have the largest impact on total cost are at some point fixed and become constraints with respect to the remaining aspects of the design [2-5].

The different types of material handling equipment can be classified into five major categories: transport equipment, positioning equipment, unit load formation equipment, storage, and identification and control equipment [1].

1.1 . Research Problem Statement

The use of 16-ton forklift trucks within indoor manufacturing industries poses health dangers to employees since the exhaust fumes of an internal combustion engine are toxic and has the added effects of Carbon Monoxide (CO) poisoning. Carbon monoxide (CO) is odourless, tasteless, colourless, non-irritating and cannot be detected by any of the senses. Because it cannot be detected, employees can be exposed to very high levels without realizing there is a problem. Therefore, this dissertation is aimed at designing a new handling system that will be hydraulically operated and powered by an electrical source (e.g. battery, motor etc.). In coming up with the system, it is believed that it will lower the rate of cost of Carbon Monoxide (CO) workers' compensation claims in South Africa. The development and integration of electro-hydraulic systems will play a key role in coming up with a new MHS that will align with the principles of industry 4.0.

The forklift, due to space availability is damaging workshop facilities as it moves from one place to another carrying bigger loads. The 16-ton forklift currently spans more space than that available, i.e. the forklift's turning radius is not favourable within an 11-m wide travelling passage (as compared to Barloworld's facility dimensions). The workshop doors are located between the workshop's structural beams, i.e. if the facility damage issue was to be solved by means of widening the doors; it would cost the company more money because the structural beams will also need to be restructured.

1.2 . Hypothesis

The replacement of fossil fuel forklifts with *electrically powered tri-adjustable heavy-duty handling system will reduce both cost to company and risk to worker's health due to a decrease in CO emission.* The design and development of the new system *will play an important role in the integration of electronics, computer science and mechanical engineering* thus aligning to industry 4.0 principles.

1.3 . Research Aim

The project motivation is to design a portable eco-friendly automated industrial/heavy duty handling system that can lift, lower, transport and store goods and products without damaging the products itself and workshop facilities that is electro-hydraulically driven. The design and development of the new proposed automated system must be based on industry 4.0 principles.

1.4 . Research Key Questions

The key questions that arise are:

1. How much will the design and development of the new system cost?
2. Will the new system be safe to operate?
3. Will the new system be economically friendly and easy to be maintained?
4. Will the new system damage workshop facilities and poses health risks to operators and/or workers?
5. Will the new proposed design system align with Industry 4.0 principles?

1.5 . Research Objectives

The objectives of the research are to:

1. Investigate types of loads and their load capacity that will be handled by the new handling system,
2. Conduct literature review on the concept of Industry 4.0 initiation and how it applies to heavy duty facility handling systems,
3. Determine standard operation procedures for the new handling system aligning with current workshop facilities and operations,
4. Populate health and safety measures for the use of the new handling system,
5. Make sure that the new system aligns with the principles of ergonomics and that is user friendly,
6. Come up with a document that will fulfil engineering design criteria and promote engineering education,
7. Developing a new system design and creating technical drawing designs using Autodesk Inventor Professional,
8. Conduct simulations through Autodesk Inventor stress analysis,
9. Design and develop electro-hydraulic system circuits,
10. Validate vehicle dynamics of the new design system.

1.6 . Project Justifications

The new design must comply with OHS requirements and be user friendly. This document is again, aimed at delivering a new design system that is much smaller than a 16-ton forklift truck and is not power driven by an internal combustion engine. A combination of electrical & hydraulic components will be considered for the development of a new design.

The project aim is to design a new system/device that can lift/lower and transport earth moving equipment such as 16 to 20-cylinder engines. This project will play a leading role in the development, application and transfer of processes and technologies for the construction, maintenance, and management of BRC material handling and internal logistics.

- Adhere to South African Occupational Health and Safety acts and standards & driven machinery regulation 18, as shown in Appendix A.
- The selections of steel materials must be of South African standards
- The system must be fit for BRC operations; be able lift $4 \times 2.3 \times 2.5m$ size loads with S.W.L of 20 Ton.
- The system must be usable and flexible, thus be able to manoeuvre within BRC's workshops.

Going forward, a CAD program (Autodesk Inventor Professional) will be used to generate conceptual designs and drawings and for analysis of static and dynamic stress of key components and frames. Vehicle dynamics equations and theory will be used for projected motions, steering calculations, and turning radius. Thorough research will be done on machine stability, hoist mechanism, factors of safety on heavy duty handling systems to align with industry 4.0 principles.

Again, the principles, laws and equations of thermodynamics and fluid mechanics will be used for construction of hydraulic circuit and power pack of the new system. As the system is desired to be power driven by an electrical energy source, the study of digital electronics and electrical machines will be done to formulate an electrical and electronic circuit for the distribution of electrical power and signals to solenoid valves, hydraulic pump, frequency drives and AC motor and again aligning with industry 4.0 principles.

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1.7 . Proposed Design Specification and Criteria

A Product design specification is a guideline of the design. It focuses on the factors that are important, limitations of the design and the criteria of the design.

Below are major considerations in the design of a new system.

- The system must be able to lift a 20-cylinder engine plus shipping stand.
- The system must not topple; it must be stable.
- The system must not be operated at high speeds.
- The system must fit within BRC workshop premises with zero damage to the facility.
- The system must be operated by trained personnel.
- The system must not rupture

Table 1 - Proposed Design Specification & Criteria Table

Loading Type	➢ Heavy duty loading to light duty
Power Requirements	➢ Hydraulically driven ➢ Overall required power, 218 kW, max Torque 775 N.m @ 2300 rpm
Expected Speed of Device	➢ Walking speed – not more than 5 km/h during operation.
Operational Environment	➢ Typical workshop and outdoor conditions. ➢ Room and outdoor temperature. ➢ Standard atmospheric pressure, 101.3 Kpa.

1.7.1. Operational and Support Personnel and Required Skills

- Training and certification will be provided to those who will be authorized to operate the equipment.
- Service support officer will be in-charge of the equipment.

1.7.2. Quality and reliability

Although quality and reliability are hard to quantify. The equipment must be of quality, thus must withstand the load without permanent deformation. The equipment must be reliable, thus deliver in time.

1.7.3. Manufacturability

- Ease of manufacturing. Stability of the frames must be considered during the design and manufacturing phase and standard rolled steel sections must be used.

1.7.4. Materials

- Structural steel is a pre-request for the construction of the lifting frame. Toxic materials should not be used. Thus, have negative impact on environment. Standard parts must be used were necessary.

1.7.5. Cost

- For the maximum number of client/ customers to be able to purchase the 20-ton automated handling system. Every effort should be made to keep its cost at a bare minimum. The retail cost should be no more than R750 000.

1.7.6. Turning ability

- The turning radius should be held to a bare minimum, not more than 8m. Turning should be accomplished without damage to floor and workshop doors.

1.7.7. Ease of use

- The machine must be easy to operate. This is necessary for safe and efficient operation of the device.

1.7.8. Machine safety

- The system will include an emergency button safety system.

1.7.9. Maintenance access and aid

- Access of major items for repair and maintenance, grease accessibility
- The device must be inspected before used from the day of purchase.
- After testing all hydraulics components must be flushed or cleaned, be for final assembly.
- After completion, a set of trials will be conducted, to prove functionality

1.7.10. New system's overall sizes

- 2.9 m wide
- 4.9 m long
- 3.91 m high

1.8. Industry 4.0 principles in the Field of Heavy-Duty Lifting Industries.

The world has grown closer; new data architecture has bridged immense spaces. A global network has emerged in which people and their environment and machines can communicate continuously. This has led to a high standard of safety comfort and efficiency and has changed society in people's daily lives. Most of the work processes are coordinated by data streams. The entire lifecycle of a product is shaped by automated and highly networked processes. The concept production, delivery and service are digitally guided and share all their process information. People and intelligent machines cooperate efficiently. Real and digitalized process has come together in one unit. The material handling system can communicate with each other and then assemble the goods. Therefore, it is significant to have an efficient and reliable material handling system at first so that it can be developed to be smart and automated to meet today's innovation and standardization and customer satisfaction [1-2].

1.9. The Significance of the Research

South African manufacturing industries faces challenges where in heavy duty handling systems within indoor operations they use MHS that uses ICE, thus, such MHSs poses health risks to workers since ICEs produces exhaust fumes (CO) when running. Therefore, this research provides a technique for possible solutions to resolving the abovementioned problem.

The research is relevant in a manner that, through the development of the new system's design as well as simulation and material selection' verification, the use of ICE within indoor manufacturing can be eliminated and be replaced with an electro-hydraulically powered system. Therefore, this research provides a solution that will assist South African manufacturing industries in preventing workers from getting exposed to harmful exhaust fumes (CO) and again promoting OHS standards of workers.

Again, this research plays an important role in the integration of electronics, computer science and mechanical engineering. The manufacturing industries totally depend on the integration of computer and electronics technologies for better products and processes; therefore, this study have great potential in the development of Mechatronics discipline.

CHAPTER TWO

LITERATURE REVIEW

2. Chapter Overview

The present study is focused on improvements in internal materials handling management, approaching the case of a large company in the automotive industry. Materials handling is intrinsically associated with production flow. Because of this, it has direct influence on transit time, resources usage, and service levels. The objective is to evaluate, in a systematic way, the impact of implemented changes in materials handling management on the internal customers' perceptions of cost, safety in service, service reliability, agility and overall satisfaction. Materials handling management is among many factors that contribute to improve a company's performance [4].

The different types of material handling equipment can be classified into five major categories: transport equipment, positioning equipment, unit load formation equipment, storage, and identification and control equipment [4].

2.1. Material Handling Types

Different types of MH are as follows,

2.1.1. Transport Equipment.

Equipment used to move material from one location to another (e.g., between workplaces, between a loading dock and a storage area, etc.). The major subcategories of transport equipment are conveyors, cranes, and industrial trucks. Material can also be transported manually using no equipment [4].

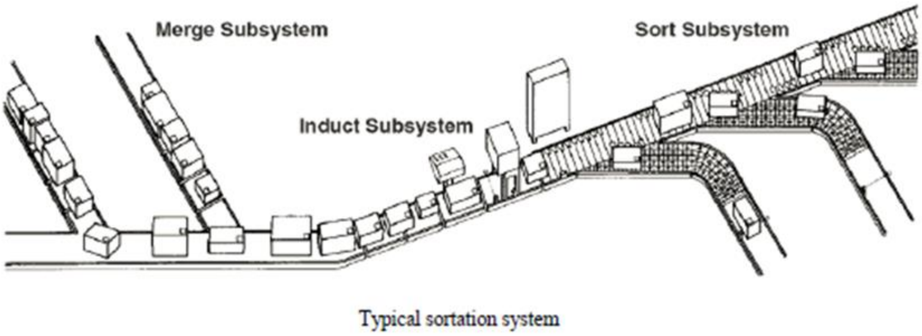


Figure 1 – Conveyors [4].

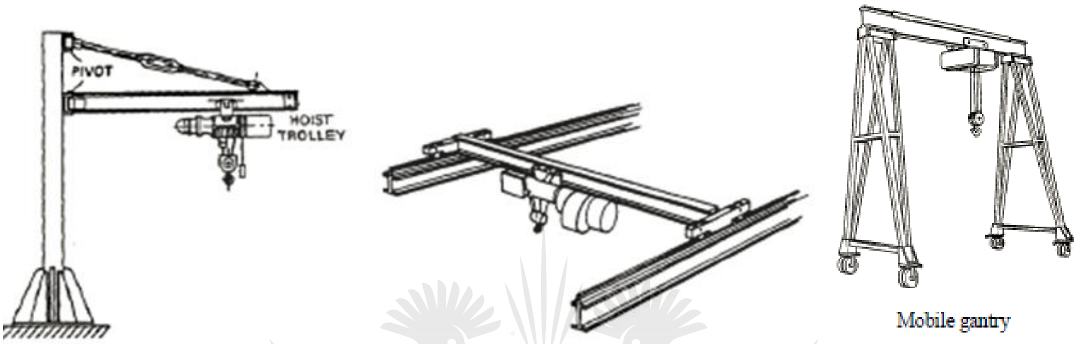


Figure 2 - Jib crane, Bridge/over-head crane and Gantry crane [4].

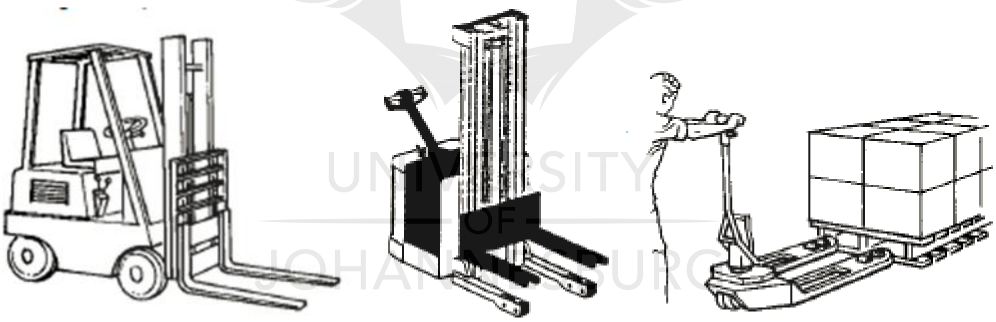


Figure 3 - Forklift truck, Powered walkie stacker and Manual pallet jack [4].

2.1.2. Positioning Equipment.

Equipment used to handle material at a single location (e.g., to feed and/or manipulate materials so that are in the correct position for subsequent handling, machining, transport, or storage). Unlike transport equipment, positioning equipment is usually used for handling at a single workplace. Material can also be positioned manually using no equipment [4].

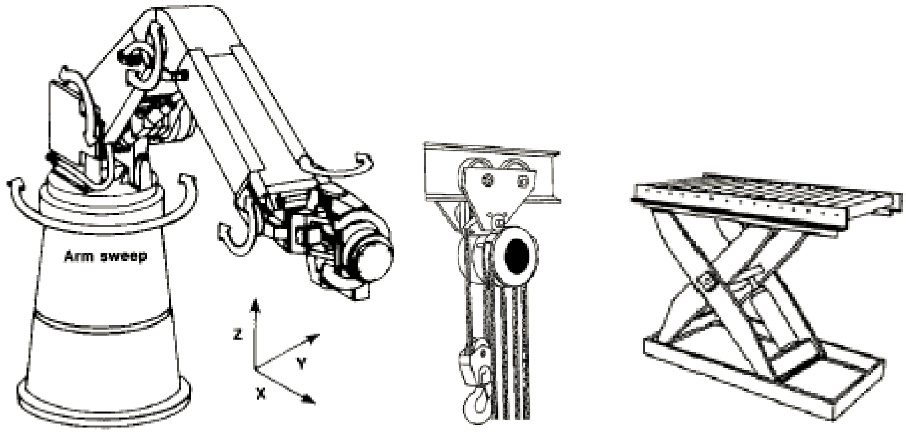


Figure 4 - Industrial Robot, Hoist, and Lift/tilt/turn table, respectively [4].

2.1.3. Unit Load Formation Equipment.

Equipment used to restrict materials so that they maintain their integrity when handled a single load during transport and for storage. If materials are self-restraining (e.g., a single part or interlocking parts), then they can be formed into a unit load with no equipment.

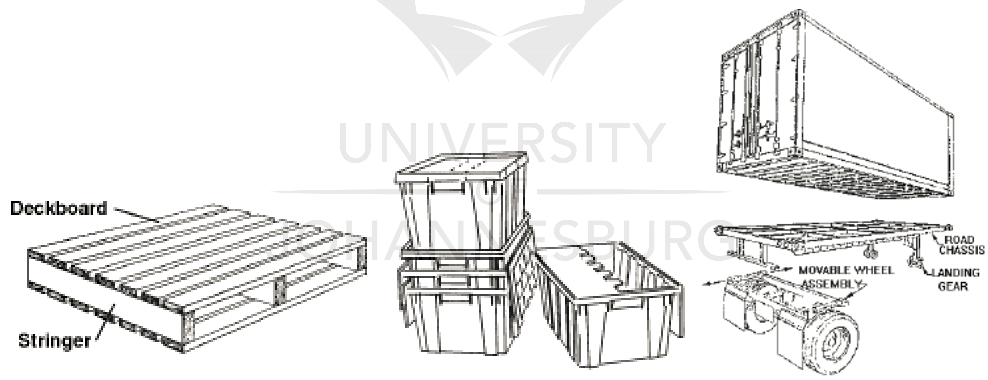


Figure 5 - Pallets, Tote pans, and Intermodal containers [4].

2.1.4. Storage Equipment.

Figure 6 elaborates equipment used for holding or buffering materials over a period. Some storage equipment may include the transport of materials (e.g. storage carousels). If materials are block stacked directly on the floor, then no storage equipment is required.

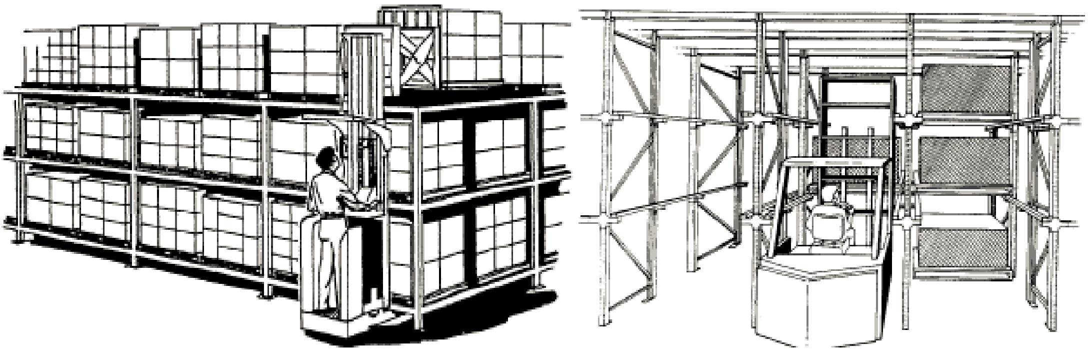


Figure 6 - Double-deep rack and Drive-through rack [4].

2.1.5. Identification and Control Equipment.

Equipment used to collect and communicate the information that is used to coordinate the flow of materials within a facility and between a facility and its suppliers and customers. The identification of materials and associated control can be performed manually with no specialized equipment [4].

Table 2 - Handling equipment categories [5].

Positioning Equipment	**Unit Load Formation Equipment**	**Storage Equipment**	**Identification and Control Equipment**
1. Manual (no equipment)	1. Self-restraining (no equipment)	1. Block stacking (no equipment)	1. Manual (no equipment)
2. Lift/tilt/turn table	2. Pallets	2. Selective pallet rack	2. Bar codes
3. Dock leveler	3. Skids	3. Drive-in rack	3. Radio frequency identification tags
4. Ball transfer table	4. Slipsheets	4. Drive-through rack	4. Voice recognition
5. Rotary index table	5. Tote pans	5. Push-back rack	5. Magnetic stripes
6. Parts feeder	6. Pallet/skid boxes	6. Flow-through rack	6. Machine vision
7. Air film device	7. Bins/baskets/racks	7. Sliding rack	7. Portable data terminals
8. Hoist	8. Cartons	8. Cantilever rack	
9. Balancer	9. Bags	9. Stacking frame	
10. Manipulator	10. Bulk load containers	10. Bin shelving	
11. Industrial robot	11. Crates	11. Storage drawers	
	12. Intermodal containers	12. Storage carousel	
	13. Strapping/tape/glue	13. Vertical lift module	
	14. Shrink-wrap/ stretch-wrap	14. A-frame	

Table 3 - Transportation equipment range [5].

Transport Equipment			
A. Conveyors	**B. Cranes**	**C. Industrial Trucks**	**D. No Equipment**
1. Chute conveyor	1. Jib crane	1. Hand truck	1. Manual
2. Wheel conveyor	2. Bridge crane	2. Pallet jack	
3. Roller conveyor	3. Gantry crane	3. Walkie stacker	
4. Chain conveyor	4. Stacker crane	4. Pallet truck	
5. Slat conveyor		5. Platform truck	
6. Flat belt conveyor		6. Counterbalanced lift truck	
7. Magnetic belt conveyor		7. Narrow-aisle straddle truck	
8. Troughed belt conveyor		8. Narrow-aisle reach truck	
9. Bucket conveyor		9. Turret truck	
10. Vibrating conveyor		10. Order picker	
11. Screw conveyor		11. Sideloader	
12. Pneumatic conveyor		12. Tractor-trailer	
13. Vertical conveyor		13. Personnel and burden carrier	
14. Cart-on-track conveyor		14. Automatic guided vehicle	
15. Tow conveyor			
16. Trolley conveyor			
17. Power-and-free conveyor			
18. Monorail			
19. Sortation conveyor			

Transport equipment (see Table 2) is used to move material from one location to another, while positioning equipment is used to manipulate material at a single location. The major subcategories of transport equipment are conveyors, cranes, and industrial trucks. Material can also be transported manually using no equipment [4,5].

The following general equipment characteristics can be used to describe the functional differences between conveyors, cranes, and industrial trucks (see Table 3):

Path: Fixed - move between two specific points

Variable - move between a large variety of points

Area: Restricted - move restricted to a limited area

Unrestricted - unlimited area of movement [4,5].

Move frequency: Low - low number of moves per period, or intermittent moves

High - high number of moves per period

Adjacent move: Yes - move is between adjacent activities

No—move is between activities that are not adjacent [4,5].

Table 4 - Transport equipment characteristics [5].

Transport Equipment Characteristics						
Path	Fixed			Variable		
Area	Restricted			Restricted		Unrestricted
Frequency	High	Low		High	Low	-
Adjacent	-	Yes	No	-	-	-
Equipment category	Conveyor	Conveyor	Industrial Truck/Crane	Industrial Truck	Crane	Industrial Truck

2.6. Principles of Material Handling

Although there are no definite "rules" that can be followed when designing an effective Material Handling System, the following "Ten Principles of Material Handling," as compiled by the College-Industry Council on Material Handling Education (CIC-MHE) in cooperation with the Material Handling Institute (MHI) [4,5].

This represent the culmination of many years of accumulated experience and knowledge of many practitioners and students of material handling: [4,5].

- Planning Principle. All MH should be the result of a deliberate plan where the needs, performance objectives, and functional specification of the proposed methods are completely defined at the outset.
- Standardization Principle. MH methods, equipment, controls, and software should be standardized within the limits of achieving overall performance objectives and without sacrificing needed flexibility, modularity, and throughput.

- Work Principle. MH work (defined as material flow multiplied by the distance moved) should be minimized without sacrificing productivity or the level of service required of the operation.
- Ergonomic Principle. Human capabilities and limitations must be recognized and respected in the design of MH tasks and equipment to ensure safe and effective operations.
- Unit Load Principle. Unit loads shall be appropriately sized and configured in a way that achieves the material flow and inventory objectives at each stage in the supply chain.
- Space Utilization Principle. Effective and efficient use must be made of all available (cubic) space.
- System Principle. Material movement and storage activities should be fully integrated to form a coordinated, operational system which spans receiving, inspection, storage, production, assembly, packaging, unitizing, order selection, shipping, and transportation, and the handling of returns.
- Automation Principle. MH operations should be mechanized and/or automated where feasible to improve operational efficiency, increase responsiveness, improve consistency and predictability, decrease operating costs, and to eliminate repetitive or potentially unsafe manual labour.
- Environmental Principle. Environmental impact and energy consumption should be considered as criteria when designing or selecting alternative equipment and MHS.
- Life Cycle Cost Principle. A thorough economic analysis should account for the entire life cycle of all MHE and resulting systems [3].

2.7. Characteristics of Materials

The characteristics of materials affecting handling include the following: size (width, depth, height); weight (weight per item, or per unit volume); shape (round, square, long, rectangular, irregular); and other (slippery, fragile, sticky, explosive, frozen), as illustrated in Table 4 [1-5].

Table 5 - Material categories [4].

Material Categories			
Physical State			
Material Category	***Solid***	***Liquid***	***Gas***
Individual units	Part, subassembly	-	-
Containerized items	Carton, bag, tote, box, pallet, bin	Barrel	Cylinder
Bulk materials	Sand, cement, coal, granular products	Liquid chemicals, solvents, gasoline	Oxygen, nitrogen, carbon dioxide

The impact of the material category listed in Table 5 on the type of MH equipment is as follows:

- Individual units and containerized items ⇒ discrete material flow ⇒ unit loads ⇒ unit handling equipment
- Bulk materials ⇒ continuous material flow ⇒ bulk handling equipment

2.8. Three Types of MHS that are Considered for this Research

2.8.1. Transport Equipment

A) Forklift Truck

A forklift (also called a lift truck, a fork truck, or a forklift truck) is a powered industrial truck used to lift and move materials within short distances, please as shown in Figure 7 [1].

Figure 7 – 16 ton Forklift truck [1]

B) Reach Stacker

A reach stacker (see Figure 8) is a vehicle used for handling intermodal cargo containers in small terminals or medium-sized ports. Reach stackers can transport a container short distances very quickly and pile them in various rows depending on its access [2].

Figure 8 - Reach stacker [2]

C) Straddle Carrier

A straddle carrier (see figure 9) is a non-road going vehicle for use in port terminals and intermodal yards used for stacking and moving ISO standard containers. Straddles pick and carry containers while straddling their load and connecting to the top lifting points via a container spreader [3].

Figure 9 - Straddle carrier [3]

2.8.2. **Positioning Equipment** (hoists or hydraulics)

A) Jib Crane

A jib crane (see Figure 10) is a type of crane where a horizontal member (jib or boom), supporting a moveable hoist, is fixed to a wall or to a floor-mounted pillar. Jib cranes are used in industrial premises and on military vehicles. The jib may swing through an arc, to give additional lateral movement, or be fixed [4].

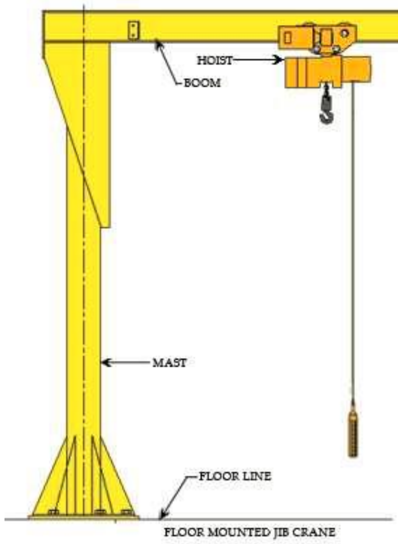


Figure 10 -- Jib Crane [4]

B) Gantry Crane

Gantry crane (see Figure 11) means a crane like an overhead crane except that the bridge for carrying the trolley or trolleys is rigidly supported on two or more legs running on fixed rails or another runway [3].

Figure 11 - Gantry crane [3].

2.9.Machine Stability Research

Stability: - For stability, the sum of all moments of any point such as the base of the crane must equate to zero. In practice, the magnitude of load that is permitted to be lifted (called the "rated load" in the US) is some value less than the load that will cause the crane to tip (providing a safety margin). Standards for cranes mounted on ships or offshore platforms are somewhat stricter because of the dynamic load on the crane due to vessel motion. Additionally, the stability of the vessel or platform must be considered. For stationary pedestal or kingpost mounted cranes, the moment created by the boom, jib, and load is resisted by the pedestal base or kingpost. Stress within the base must be less than the yield stress of the material or the crane will fail [1-3].

2.9.1. Counterbalance Handling Equipment

These types of material handling equipment generally have:

- The body with its counterbalance and cage rigidly attached to the front or drive axle.
- The mast pivoted at or near the front axle.
- The steer axle pivoted about its centre so that the steer tyres remain in contact with the ground where there are small variations in the level of the operating surface; and
- Brakes fitted to the front drive axle only [1-3].

2.9.2. Centre of mass Research

Any physical object has a point located in three dimensions where it acts as though all its mass is located. This is known as its centre of mass. It is a point about which the forklift would balance if placed on top of a pointed support [2].

When a counterbalance handling equipment is stationary, the only force acting on this point is the force of gravity vertically down. For a stationary counterbalance handling equipment, provided this centre of mass is within the stability triangle, the equipment will neither tip forwards nor sideways [3].

If sufficient load is added the handling equipment will reach a point where it tips forward. This generally occurs if an operator tries to lift a load that is much too heavy for the forklift, and the steer axle lifts off the ground [1-3].

2.10. Power Transmission Research

The development of our present level of technology has depended on the evolution of methods for the generation, distribution, and utilization of power. Fluid power technology plays an important role in this task and promises to be even more important in the future [1-3].

2.10.1. Methods of Transmitting Power

Most of contemporary power transmission systems can be classified as electrical, mechanical, or fluid. Fluid power systems can be further divided into pneumatic and hydraulic systems, depending on the fluid medium used to transmit force. The fluids employed in pneumatic power and control systems are gases which are characterized by high compressibility. In contrast, hydraulic fluids are relatively incompressible liquids.

A) Electrical Power Transmission

Power is transmitted electrically by imposing an electromagnetic field on a conductor. Electric systems are especially suitable for power transmission over long distances and are best applicable to low-power operations. Magnetic saturation, a fundamental limitation of electrical machines, limits the torque developed by an electric motor. Material limitations also affect the speed with which electrical servomechanisms can respond. Heat dissipation is a problem of frequent importance in electrical power transmission, please as shown in Figure 12 for an example of electrical power transmission [1-3].

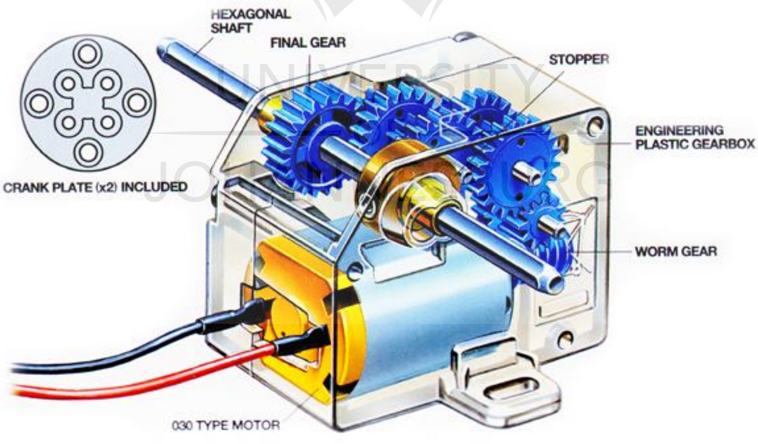


Figure 12 - Electrical Power Transmission [4].

B) Mechanical Power Transmission

Mechanical power transmission systems employ a variety of kinematic mechanisms such as belts, chains, pulleys, sprockets, gear trains, bar linkages, and cams. They are suitable for the transmission of motion and force over relatively short distances. The disadvantages of mechanical systems include lubrication problems, limited speed and torque control capabilities, uneven force distribution, and relatively large space requirements, Figure 13 illustrates an example of mechanical power transmission [1-3].

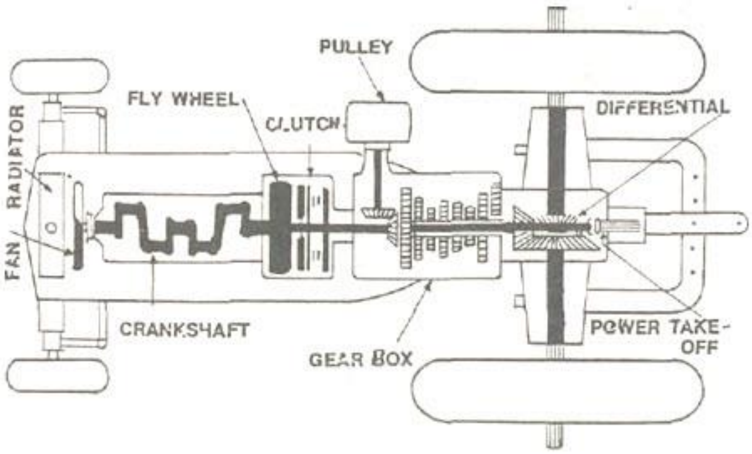


Figure 13 - Simple Mechanical Power Transmission [4]

C) Pneumatic Power Transmission

Pneumatic power is transmitted by the pressure and flow of compressed gases, (see Figure 14). The most common gas used is air. Pneumatic systems use simple equipment, have small transmission lines, and do not present a fire hazard. Disadvantages include a high fluid compressibility and a small power-to-size ratio of components. Pneumatic power systems are more elastic than mechanical systems and are very sensitive to small changes in pressure or flow. For this reason, they are especially suited for pilot or control systems [5].

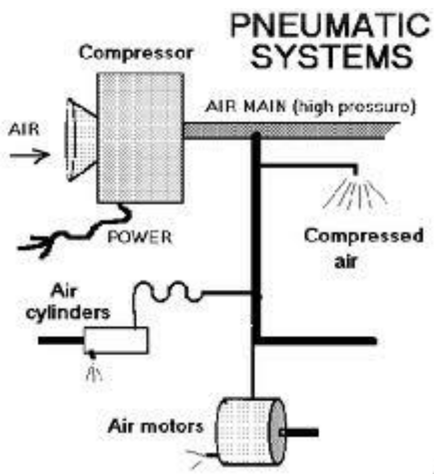


Figure 14 - Pneumatic Power Transmission system [5].

D) Hydraulic Power Transmission

Hydraulic power (see figure 15) is transmitted by the pressure and flow of liquids. For many years' petroleum oils were the most common liquids, but other types of liquids are now finding widespread use. Hydraulic systems are mechanically stiff and can be designed to give fast operation and move very large loads. They can be employed over greater distances than mechanical types but not as far as electrical systems [4].

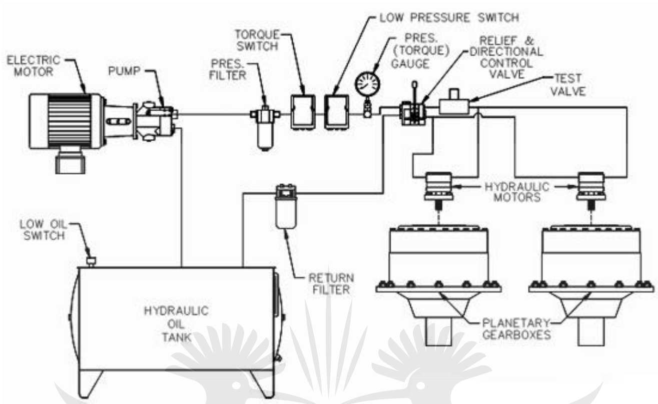


Figure 15 - Hydraulic Power transmission schematic diagram [5].

2.11. Selected Power Transmission for New System Design

Out of the four methods of power transmission, Hydraulic power transmission method has been chosen for the new design system development.

2.8. Hydraulic Power System Research

The new system design is desired to be operated under severe conditions, thus heavy-duty handling environment. Hydraulic power systems best suites the new system design's operation and functionality enhancing it to be able to handle 30-ton load capacity and transporting it.

2.8.1. Advantages of Hydraulic Power Systems:

- Large torques and forces transmitted to any part of a machine.
- Cushioning for shock loads.
- Reversible, infinitely variable speed and load control.
- Completely automatic operations.
- Accurate position control for linear and rotary elements.

- Power linkage where kinematic linkage is impractical.
- Reduction of wear by the self-lubrication action of the transmission medium.
- Safe power system operation for both operator and machine [4, 5].

2.8.2. Major Disadvantages of Hydraulic Systems are:

- Impairment of system operation by contamination,
- Hydraulic fluid leakage.
- Fire hazards with flammable hydraulic fluids [4, 5].

2.8.3. Hydraulic Fluid Functions

The functions of a hydraulic fluid are to transmit force applied at one point in the system to some other location and to produce any desired change in direction or magnitude of this force. To carry out this function in the most efficient manner, the hydraulic fluid must be relatively incompressible and must flow readily. In addition, the hydraulic fluid must perform certain other functions-such as lubrication and cooling-which are secondary in nature but are important to the overall operation of the hydraulic system [4, 5].

2.8.4. Principles of Hydraulics Research

A) Generation and use of Fluid Power

The use of hydraulic fluids to generate and transmit power is based upon physical laws which govern the mechanics of liquids. The principles of fluid mechanics, including both hydrostatics and fluid dynamics, have been developed over a period of several centuries and now constitute a fundamental branch of science and engineering. A knowledge of the application of these principles to the design and use of fluid power systems can be obtained by a study of any of several references drawn from the vast literature of fluid mechanics [5].

B) Fluid Power Circuits

The application of fluid power (see figure 16) requires some type of fluid circuit. Many different circuit designs are possible for a given application. However, most hydraulic circuits represent some variation of a few basic circuit designs such as pump circuits, fluid motor circuits, accumulator or intensifier circuits, and control circuits. All hydraulic circuits consist of some combination of six basic components: (1) a source of pressure, e.g., a pump; (2) a means of converting pressure into mechanical motion, e.g., a hydraulic motor or actuator; (3) fluid-transfer piping; (4) pressure, directional, and flow controls; (5) a fluid reservoir; and (6) a hydraulic fluid. The output of the hydraulic circuit is determined by the way the various components are arranged [5].

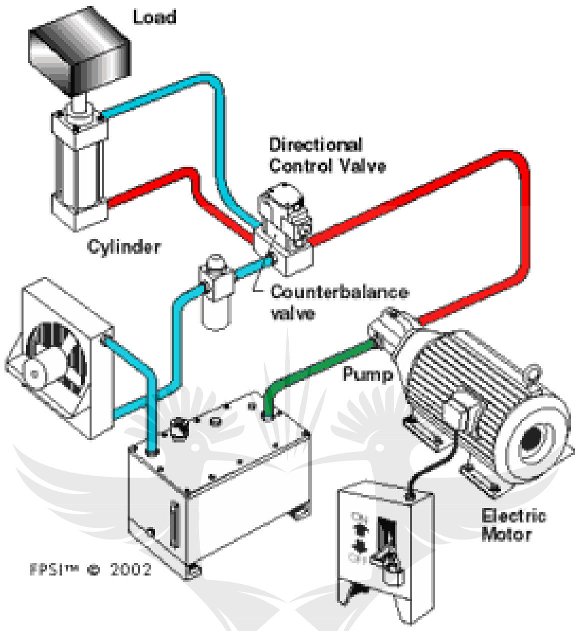


Figure 16 – Fluid power circuit illustration [5].

C) Uses of Hydraulic Power

The way hydraulic power can be used is limited primarily by the imagination of the designer. Hydraulic power has found its most extensive use in manufacturing and construction machinery. Fluid-power operated presses and material-handling machinery are common fixtures in any production plant. In construction and earth-moving industries, hydraulic power is used on almost every piece of equipment. Other industries making extensive use of fluid power are aerospace, agriculture, petroleum, automotive, chemical, and food processing [5].

D) Requirements for Hydraulic Fluids

The hydraulic fluid is an essential and important component of any hydraulic power or control system. No other component of the circuit must perform as many functions or meet as many requirements as the hydraulic fluid. The hydraulic fluid must not only provide a medium for efficient power transmission, but it must also lubricate, cool, protect from corrosion, not leak excessively, and perform numerous other functions depending on the system design. However, even if a hydraulic fluid can adequately perform these system functions, it may still be less than satisfactory in terms of usage and compatibility factors. In many hydraulic systems, it is necessary that the hydraulic fluid be nontoxic and fire-resistant. It must be compatible with the structural materials of the system. The hydraulic fluid should exhibit stable physical properties during a suitable period of use. It should be easy to handle when in use and in storage, and it is desirable, of course, that it be readily available and inexpensive.

The selection of a hydraulic fluid is further complicated by the vast number of liquids currently available. These range from water and mineral oils to special purpose synthetic liquids. It is thus necessary for the system designer to have at least an elementary understanding of the terminology prevalent in the specification of hydraulic fluids [5].

2.8.5. System Dependency of the Hydraulic Fluid - Research

A) Temperature

Temperature is a system parameter rather than a characteristic of the fluid. However, the physical properties of hydraulic fluids are influenced by the operating temperature. High temperature can cause a decrease in viscosity and lubricity, resulting in increased leakage through seals and detrimental friction and wear. Many hydraulic fluids experience molecular breakdown at elevated temperatures. Viscosity increases with decreasing temperature, and thus the lowest operating temperature for a given liquid is that corresponding to the maximum viscosity which can be satisfactorily accommodated by the system.

Hence, an important requisite in the selection of hydraulic fluids is a thorough knowledge of the storage temperature, the average operating temperature, the high and low operating temperatures, and the temperatures of local system hot spots. With these known, it then becomes necessary to know the way the liquid properties vary within the system temperature range [4, 5].

B) Viscosity

Viscosity, often referred to as the most important single property of a hydraulic fluid, is the property which characterizes the flow resistance of liquid. Low viscosity liquids transmit power more effectively, whereas high viscosity is required to lubricate and to reduce leakage. Thus, the allowable viscosity range depends on a compromise between the power-transmission characteristics on the one hand and the sealing and lubricating properties on the other.

Viscosity depends upon temperature and pressure, and generally increases with decreasing temperature or increasing pressure. The viscosity index (V.I.) is a measure of the temperature dependence. Liquids with a high viscosity index exhibit a smaller variation of viscosity with temperature than do liquids with a low V.I. Low-viscosity liquid are less affected by pressure than high-viscosity liquids. Liquids which exhibit a large variation of viscosity with temperature usually exhibit a large viscosity change with pressure. Viscosity affects many operational factors in a hydraulic system-mechanical friction, fluid friction, pump slippage, cavitation, leakage, power consumption, and system control ability. The use of a hydraulic fluid with a low viscosity can lead to increased pump slippage, excessive wear of moving parts, and hydraulic fluid loss due to leakage. A viscosity which is too high will cause increased pressure loss and power consumption and, because of liquid friction, can lead to excessive system temperatures [4, 5].

C) Compatibility with System Materials

Chemical compatibility of a hydraulic fluid with the system materials sometimes requires compromises in the selection of the hydraulic fluid or the materials of construction. The hydraulic fluid should be chemically inert and should not react with materials of the system or the environment. In turn, the construction materials should not affect the properties of the hydraulic fluid [4].

Corrosion prevention is one of the many functions of the hydraulic fluid. Air and moisture are always present, to some degree, in hydraulic systems. Therefore, most hydraulic fluids have a rust inhibitor and/or a metal deactivator which coats the metal surfaces.

Copper is an undesirable material for hydraulic systems because it serves as a catalyst for the oxidation of many hydraulic fluids. Liquid oxidation rate increases with increasing temperature and is enhanced by the presence of water, air, and solid contaminants in the fluid. Chemical additives are commonly used in hydraulic fluids to control the rate of oxidation [4].

Seal materials often present a difficult design problem from the viewpoint of compatibility with hydraulic fluids. Natural rubber reacts in some manner with nearly all hydraulic oils. The reaction of synthetic rubbers depends upon the type of synthetic and the liquid to which it is exposed. The aniline point can be used as a relative indication of the effect of mineral oils on rubber. Oils with high aniline points generally cause less swelling or shrinking than oils with low aniline points. As mentioned above, compatibility is not solely a problem of selecting a hydraulic fluid. When a hydraulic fluid is found that has desirable performance characteristics but is chemically incompatible with some system material, a better overall system is often obtained if the construction material is changed rather than the hydraulic fluid. However, in many military applications, a change in construction material is not easily accomplished. It has often been necessary to change the hydraulic fluid or develop a new hydraulic fluid for existing equipment [4, 5].

D) Hydraulic System Accuracy, Speed of Response, and Stability

The type of hydraulic fluid used in a hydraulic system is an important factor in determining system accuracy, response speed, and stability. These characteristics of a system are not determined by any one property of a liquid but depend on the combination of several properties, especially viscosity and compressibility. If the hydraulic fluid is one of the more compressible types, much of the energy supplied to the system is used in deforming the liquid with a resultant loss in response speed and accuracy of system component operation. Also, if liquid transmission lines are long, compression delays in control signals can result in interference of various signals and erratic component response. If a hydraulic fluid having too high a viscosity is used, flow resistance and pressure drops in the system increase and operation becomes sluggish. If the viscosity is too low, control precision may be lost [4].

E) Fluid Stability (Temperature and Shear)

The stability of a hydraulic fluid determines the length of time during which it remains useful either in service or in storage. A stable liquid exhibits only small changes in characteristics over a suitable period. The degree to which a hydraulic fluid is stable depends upon two factors: (1) its tendency to react with the environment, and (2) the changes induced by operational use.

The oxidation stability of a hydraulic fluid is measured by its tendency to decompose or polymerize. Oxidation reactions are markedly accelerated by an increase in temperature. Over a prolonged period, accumulation of oxidation products can cause deterioration of the hydraulic fluid appearing as increased viscosity and sludge deposits. Since all liquids oxidize to some extent at all temperatures, a hydraulic fluid is considered to possess oxidation stability if the changes induced by oxidation over a reasonable period do not render the hydraulic fluid unsatisfactory for operational use [4]. Changes in viscosity can also result from (1) thermal decomposition at local hot spots, and (2) the breakdown of molecules due to high rates of shear.

Like the other factors discussed, stability requirements depend upon system design as well as hydraulic fluid selection. For example, oxidation and hydrolytic stability of a given hydraulic fluid can be extended if the hydraulic system is designed to minimize the amount of air and water which can enter the fluid circuit [5].

F) Lubricity

The hydraulic fluid must serve as a lubricant between moving parts of the system to minimize friction and wear. To do so, it must have a suitable viscosity and must possess adequate lubricity. The term "lubricity" refers to the ability of a liquid to reduce friction and prevent wear under even the most severe circumstances. Lubricity is a complex function that refers to the shear strength of a thin lubricating film [5].

A liquid that forms a film of low shear strength is said to have good lubricity. The ability of a liquid to form a film on a surface is important in lubrication. The film can support the loads encountered during operation. Breakdown of the lubricating film causes wear and shortens the life of the system components. In general, higher viscosity liquids are better able to maintain films than those of lower viscosity. However, system considerations other than lubrication limit the value of viscosity in some applications. Anti-wear additives provide a solution to some of these problems [5].

G) Pressure

The reduction of volume of a liquid under pressure is a measure of the compressibility of the liquid. Compressibility influences the power required by the pump, the time required to generate pressure, the speed with which the transmission and control systems respond to input, and the way energy is converted by pressure reduction. The bulk modulus is the reciprocal of the compressibility and is always a positive quantity [4]. A high bulk modulus indicates low liquid elasticity and, hence, a small spring effect when subjected to a pressure change. A liquid with high bulk modulus is desirable to obtain good dynamic performance in a hydraulic system [5].

H) Lacquer and Insoluble Material Formation

The hydraulic fluid should remain homogeneous while in use. The formation and deposit of insoluble materials on parts of the system can cause system malfunction or failure. Insoluble materials can be formed by many different processes. Oxidation, contamination, thermal degradation, hydrolytic degradation, etc., can all produce insoluble materials. Changes in the hydraulic fluid caused by the above processes can also affect the solubility of additives and result in the additives becoming insoluble. Insoluble materials can plug small orifices, reduce clearances, damage surfaces, or form deposits on working surfaces. The deposits show up as coatings, varnishes, lacquers, etc [4, 5].

2.8.6. Other Hydraulic Fluid Considerations

a) Availability

It is obviously desirable that a hydraulic fluid be readily available. If a hydraulic fluid possesses widely applicable properties and is competitive in terms of cost, it will usually be readily available [4].

b) Cost

Several factors must be considered in the evaluation of the cost of a hydraulic fluid. The original cost, the service longevity, storage costs, and rate of system leakage enter the overall cost evaluation. The purchase of an expensive hydraulic fluid is justified if its properties can result in lower ultimate system costs because of reduced replacement frequency, increased component life, or other factors. However, consideration should be given to the economy afforded by changes in system design to allow use of a less expensive hydraulic fluid [4, 5].

c) Handling

The ease with which a hydraulic fluid can be handled is important to the user and to maintenance personnel. Toxicity is perhaps the first factor to consider in evaluating handling characteristics. The hydraulic fluid, its vapor, and its decomposition products should have very low toxicity, in terms of inhalation, ingestion, or contact with the skin. Toxic liquids can be used only if extreme precautions are taken to insure no harmful effects to the operating and maintenance personnel [4,5].

d) Storage

The storage characteristics of a hydraulic fluid are closely related to chemical stability and handling characteristics. The properties of a hydraulic fluid should not deteriorate if the fluid stands in storage for long periods. Precautions should be taken to ensure that contaminants cannot enter the stored hydraulic fluid. Oxidation stability is often used as a criterion in evaluating the storage characteristics [4].

e) Contamination

A hydraulic fluid is subjected to several sources of contamination, both in use or in storage. Air and moisture can leak into the system. These contaminants promote oxidation and hydrolysis. Entrained water can also cause emulsions which, in turn, tend to collect solid impurities. It should be noted that emulsions are formed more readily in contaminated liquids than in clean ones. Solid contaminants can result from fabrication, handling, or cleaning procedures, and from wear debris. Solid contaminant particles can increase wear, accelerate corrosion, and contribute to sludge and foam formation. Oxidation products and the compounds formed by additive decomposition are contaminants. Several methods are used to remove various contaminants [4].

Filtration devices can be used to remove solid particles. Magnetic plugs and filters can remove ferrous metal particles. Storage in settling tanks allow solid particles to settle out by gravitational forces. Centrifuges are sometimes used to remove heavy contaminants. If the liquid has good remissibility properties, water can be removed after it separates from the liquid in a reservoir or storage vessel [4,5].

2.9. Exposure to Carbon Monoxide in the Workplace - Research

Carbon monoxide in workplaces can be a serious health hazard. In extreme cases it can kill. Workers have suffered from a range of short-term health effects. Some have collapsed at work and required recovery, while others have died [6].

2.9.1. What is Carbon Monoxide (CO)?

Carbon monoxide (CO) is a poisonous gas emitted by operating petrol, gas and, to a lesser extent, diesel powered motors. With the chemical formula ‘CO’, its molecules consist of one carbon atom covalently bonded to one oxygen atom [6].

Because CO is colourless, tasteless, and odourless, in poorly ventilated workplaces it has the potential to be undetected and therefore build up to dangerous and even fatal levels.

While most people can tolerate small amounts of CO without noticeable ill effects, they may not realise they have suffered harm until severe symptoms occur [6].

2.9.2. What Harm can CO Cause?

Low levels of CO may occur unnoticed in the air we breathe wherever petroleum fuels are burnt, e.g. in car parks or city streets. However, inhaling CO can cause headache, drowsiness, irritability, reduced judgement and motor skills, convulsions, unconsciousness, coma, and death [6].

In the long term, CO may cause heart and circulatory disease. It may also harm the central nervous system and affect pregnant women. Severe harm is most likely where petrol motors are run continuously in enclosed or poorly ventilated areas [6]. Physical activity will affect the worker’s breathing rate and hence also the amount of CO inhaled [6].

2.9.3. What are the Symptoms of CO Poisoning?

a) *At **high CO** concentrations, symptoms may include:*

- Severe headache.
- Decreased vigilance and impaired judgement.
- Excessive perspiration.
- Dizziness and disorientation.
- Rapid or irregular heartbeat.

- Personality changes (including aggressiveness and irritability);
- Vomiting & collapse.
- Convulsions and seizures; and coma.

b) *Symptoms at **low CO** levels may be interpreted as a non-specific viral illness and include:*

- Tightness across the forehead.
- Slight to moderate headache.
- Weakness and fatigue.
- Shortness of breath on exertion.
- Nausea; and impaired motor skills.

In severe cases CO poisoning can lead to death. Where it is suspected that a person has become ill due to inhalation of CO, medical attention should be sought immediately [6].

2.9.4. How Does CO Affect the Body?

CO, if inhaled, interferes with the movement, and use of oxygen in body tissues. It can cause chemical asphyxiation by displacing oxygen from the bloodstream [6].

Health effects may include:

- Reduced capacity to undertake physical work.
- Aggravation of pre-existing cardiovascular conditions.
- Impairing the central nervous system.
- Damaging blood vessels in the heart; and
- With pregnant women, causing harm to the foetus.

2.9.5. Where Does CO Occur?

CO is produced at any workplaces where petrol or liquefied natural gas (LNG), liquefied propane gas (LPG) or diesel motors are used to power vehicles or machinery. CO occurs because hydrocarbon fuels are seldom completely burnt in combustion motors. Poorly tuned or infrequently maintained motors are likely to produce higher and more toxic concentrations of CO [6].

Although gas motors using LNG or LPG produce significantly less CO than petrol motors, caution must still be exercised, particularly in poorly ventilated areas. Diesel motors produce much less CO then either petrol or gas. They are less of a problem because toxic diesel exhaust gases are unpleasant to inhale and a hazardous build up is easily identified and remedied.

However, diesel motors should not be run continuously in poorly ventilated enclosed areas, e.g. tractors in farm sheds. In general, hazardous CO levels will not build-up where combustion motors are used outdoors or in open spaces where there is good air movement [6].

2.9.6. Which Jobs Involve CO Hazards?

When any petrol, diesel, LPG, or LNG powered equipment is in use within confined or semi-confined areas, CO levels and adequate ventilation need to be considered. Some examples of workplace situations where CO can be hazardous are provided below [6].

- Underground car parks
- Chainsaws
- Forklifts, (see Figure 17)
- Generators, etc

Forklifts: Gas powered forklifts are preferred to petrol motors to reduce emissions in enclosed work areas. However, gas motors can also cause CO build up if poorly tuned or used for long periods in confined areas such as cool rooms and small warehouses [6].

Figure 17 - Forklift truck exhaust fumes [6].

2.9.7. What the Law says about CO

The Act says that, as far as practicable, employers must provide and maintain a work environment in which employees are not exposed to hazards. This includes providing a safe system of work, training, information, supervision, and personal protective equipment where appropriate [6].

The Act also says employees must take reasonable care of their own safety and health and avoid adversely affecting the safety and health of others. They must comply, as far as possible, with safety instructions, use the personal protective equipment provided, and report hazards or injuries [6]. The Occupational Safety and Health Regulations 1996 (the regulations) require that employers identify hazards, assess the risks, and consider controls. The regulations establish exposure standards for contaminants such as CO, outlined in the box below. These exposure standards are not to be exceeded [6].

CO exposure standard

The eight-hour time-weighted average occupational exposure standard for CO is 30 ppm (parts per million). Higher exposures are permitted for short periods of time, provided the average exposure does not exceed 30 ppm. For example, a total exposure time of 15 minutes is permitted at 200 ppm, 30 minutes at 100 ppm, and 60 minutes at 60 ppm. Exposures should never exceed 400 ppm.

Figure 18 - GOVERNMENT OF WESTERN AUSTRALIA GUIDANCE NOTE - ISBN 0-7307-7616-6 [6]

2.9.8. Manage the CO Risk

Risk to workers can be managed by:

A. Identifying work situations where CO may be a hazard – i.e. wherever fumes from machinery are present; and
B. Assessing the risk of exposure to dangerous levels of CO; and
C. Measuring CO levels.
    - in the air being breathed by the worker.
    - in a worker's blood at the end of a shift; and
    - in exhaled air at the end of a shift; and then
D. Putting controls in place [6].

In order of importance, the following controls should be used to reduce CO exposure.

- **Eliminate** the need to use CO emitting machines – e.g. in the case of concrete cutters (i.e. chasing saws), by designing buildings that require minimum cutting.
- **Substitute** with safer equipment – e.g. in enclosed or poorly ventilated areas, use electric, hydraulic, or pneumatic power sources instead of petrol or gas motors.
- **Predictive Planning** – e.g. where concrete cutters (i.e. chasing saws) are to be used during construction, do so before the roof is built.
- **Engineering controls** – e.g. exhaust ventilation, via ducted piping attached to the equipment and piped to an outdoor area, to remove CO from the source or improving ventilation with natural air flow or fans. Regular maintenance of motors will also minimise the amount of CO emitted.
- **Administrative controls** – e.g. implementing time limits on machinery use and staff rosters to keep worker exposure below harmful levels.
- **Protective equipment** – where protection is needed, air-supplied respirators must be used. Commonly available air purifying respirators are not effective against CO [6].

2.9.9. CO Information and Training

CO hazard training should enable workers to work safely and react appropriately if things go wrong.

Workers must be:

- informed of all identified hazards at the workplace; given information, instruction, training, and supervision in safe working procedures, including fitting, use, maintenance, and storage of personal protective equipment.
- where necessary, provided with information in other languages, and increased supervision when workers are from a non-English speaking background.
- able to identify hazards and report them to a supervisor, and able to recognise the symptoms of CO exposure.
- trained in emergency evacuation procedures; and
- provided with ongoing training, with regular revision of safe procedures [6].

2.10. Machine Design Research

Design is the activity in which engineers accomplish the preceding task, usually by responding to a design imperative for the required task. The design imperative is the result of a problem definition and has the following general form: "Design (subject to certain problem-solving constraints) a component, system or process that will perform a specified task (subject to certain solution constraints) optimally." [4].

The result of the engineering design process is a specification set from which a machine, process, or system may be built and operated to meet the original need. The designer's task is then to create this specification set for the manufacture, assembly, testing, installation, operation, repair, and use of a solution to a problem. Although primarily decision making and problem solving, the task is a complex activity requiring special knowledge and abilities. A designer cannot effectively operate in a vacuum, but must know, or be able to discover, information affecting the design, such as the state of the art, the custom of the industry, governmental regulations, standards, good engineering practice, user expectations, legal considerations (such as product liability), and legal design requirements [4].

In addition, an effective designer possesses the ability to make decisions; to innovate solutions to engineering problems; to exhibit knowledge of other technologies and the economics involved; to judge, promote, negotiate, and trade off; and finally, to sell an acceptable problem solution which meets the imposed constraints [5].

2.10.1. Research Design Criteria

Although the general criteria used by a designer are many, the following list addresses almost all concerns [5]:

- Function
- Safety
- Reliability
- Cost
- Manufacturability
- Marketability

The inclusion of safety and reliability at or near the level of importance of function is a recent development that has resulted from governmental regulation, expansion in the numbers of standards created, and development of product liability law, all of which occurred in the late 1960s and early 1970s [4].

Although cost is explicitly fourth on the list, its consideration permeates all the criteria just listed and is part of all design decisions. As taught and practiced in the past, design criteria emphasized function, cost, manufacturability, and marketability. Reliability was generally included as a part of functional considerations. If product safety was included, it was somewhere in the function-cost considerations [4].

Design critiques were accomplished at in-house policy committee meetings or their equivalent involving design engineers, a production representative, a materials representative, and possibly representatives of marketing and service [5].

In the current design climate, the traditional design criteria are still valid; however, the additional constraints of governmental regulations, standards, and society's desire for safety, as exemplified in product liability litigation, must be included in the design process. In addition, engineers must now be prepared to have their designs evaluated by non-designers or nontechnical people. This evaluation will not be in the inner confines of a design department by peers or supervisors, as in the past, but may be in a courtroom by a jury of nontechnical people and attorneys who have an ulterior motive for their approach or in the public arena [4].

Since such a design evaluation is generally a result of an incident which caused damage or injury, to mitigate the nontechnical evaluation, current design procedures should emphasize the following factors in addition to traditional design criteria:

- *Safety* - This is associated with all modes of product usage. In providing for safety, the priorities in design are first, if possible, to design the hazards out of the product.
- *Failure analysis* - If failure cannot be prevented, it is necessary that it be foreseen, and its consequences controlled.
- *Documentation* - Associated with the evolution of the design, documentation is developed so that it can satisfy the involved nontechnical public as to the rationale behind the design and the decisions and trade-offs that were made [4].

Additional criteria, considerations, and procedures should be included in programs to address specifically the product safety, failure, or malfunction problems which have contributed significantly to the existing product liability situation. Some of the important considerations and procedures are [4].

- **Development and utilization** of a design review system specifically emphasizing failure analysis, safety considerations, and compliance with standards and governmental regulations.
- Development of a list of **modes of operation and examination** of the product utilization

  in each mode.
- **Identification of the environments of usage** for the product, including expected uses, foreseeable misuses, and intended uses.
- **Utilization of specific design theories** emphasizing failure or malfunction analysis and safety considerations in each mode of operation [4].

Design reviews have been used extensively for improving product performance, reducing cost, and improving manufacturability. In the current product liability climate, it is very important to include, and document in the review, specific failure analysis and safety emphases as well as to check compliance with standards and governmental regulations [4].

2.10.2. Materials used in Machine Construction

a) *Cast Iron*

A hard, relatively brittle alloy of iron and carbon which can be readily cast in a mould and contains a higher proportion of carbon than steel (typically 2–4.3 per cent).

b) *Malleable Cast Iron*

Cast iron containing usually from 2 to 3 percent carbon and 1.5 to 0.8 percent silicon and produced by annealing white cast iron of this composition in order to convert hard brittle cementite to graphite in nodular form so that the material will have greater ductility than white iron or ordinary grey iron containing graphite in flake form [7].

c) *Chilled Castings*

A casting made by contacting it with something that will rapidly conduct the heat from it, such as a cool iron mould, or by sudden cooling by exposure to air or water [8].

d) Wrought Iron

A commercial form of iron that is tough, malleable, and relatively soft, contains less than 0.3 percent and usually less than 0.1 percent carbon, and carries 1 or 2 percent of slag mechanically mixed with it [9].

e) Steel

A commercial iron that contains carbon in any amount up to about 1.7 percent as an essential alloying constituent, is malleable when under suitable conditions, and is distinguished from cast iron by its malleability and lower carbon content [10].

f) Copper

A metallic chemical element that is easily formed into sheets and wires and is one of the best-known conductors of heat and electricity [11].

g) Alloys

A substance composed of two or more metals or of a metal and a non-metal intimately united usually by being fused together and dissolving in each other when molten [12].

h) Polyvinyl Chloride

Polyvinyl Chloride is a polymer of vinyl chloride used especially for electrical insulation, machinery covers, films, and pipes [13].

2.10.3. Machine Design Manufacturing Process Types

a) Forging

Forging is a manufacturing process involving the shaping of metal using localized compressive forces. The blows are delivered with a hammer (often a power hammer) or a die. Forging is often classified according to the temperature at which it is performed: cold forging (a type of cold working), warm forging, or hot forging (a type of hot working) [14].

b) Welding

Welding is a fabrication or sculptural process that joins materials, usually metals or thermoplastics, by using high heat to melt the parts together and allowing them to cool causing fusion. Welding is distinct from lower temperature metal-joining techniques such as brazing and soldering, which do not melt the base metal [15].

c) Metal Cutting

Metal casting is the process of removing unwanted material in the form of chips, from a block of metal, using cutting tool [16].

d) Surface grinding

Surface grinding is a manufacturing process which moves or grinding wheel relative a surface in a plane while a grinding wheel contacts the surface and removes a minute amount of material, such that a flat surface is created [17].

e) Surface Finishing

Surface finishing is a broad range of industrial processes that alter the surface of a manufactured item to achieve a certain property. Finishing processes may be employed to: improve appearance, adhesion, or wettability, solderability, corrosion resistance, tarnish resistance, chemical resistance, wear resistance, hardness, modify electrical conductivity, remove burrs and other surface flaws, and control the surface friction [18].

f) Drilling

Drilling is the process of cutting holes in a solid material using a rotating cutting tool. The indentation is a starting point for the drilling of the hole. Drilling is a cutting process in which a drill bit is used to cut or enlarge a hole in a solid material [19].

g) Milling

Milling is a process performed with a machine in which the cutters rotate to remove the material from the work piece present in the direction of the angle with the tool axis [20].

2.10.4. Machine Design Heat Treatment Types

Heat treatment is a group of industrial, thermal and metalworking processes used to alter the physical, and sometimes chemical, properties of a material [21].

a) Hardening

Hardening is a metallurgical metalworking process used to increase the hardness of a metal. The hardness of a metal is directly proportional to the uniaxial yield stress at the location of the imposed strain. A harder metal will have a higher resistance to plastic deformation than a less hard metal [22].

b) Tempering of Steel

In metallurgy, process of improving the characteristics of a metal, especially steel, by heating it to a high temperature, though below the melting point, then cooling it, usually in air. The process has the effect of toughening by lessening brittleness and reducing internal stresses [23].

c) Case hardening

Case hardening is a technique in which the metal surface is reinforced by the adding of a fine layer at the top of another metal alloy that is generally more durable. Case hardening steel is normally used to increase the object life. This is particularly significant for the manufacture of machine parts, carbon steel forgings, and carbon steel pinions [24].

d) Quenching

Is a rapid way of bringing metal back to room temperature after heat treatment to prevent the cooling process from dramatically changing the metal's microstructure [25].

e) Normalizing Heat Treatment

Normalizing heat treatment is a heat-treating process used to provide uniformity in grain size and microstructure in some steel grades. Normalizing is the process of heating a material to a temperature above a critical limit and then cooling in open air [26].

f) Annealing

Annealing is a heat treatment process which alters the microstructure of a material to change its mechanical or electrical properties. Typically, in steels, annealing is used to reduce hardness, increase ductility, and help eliminate internal stresses [27].

2.11. Chapter Summary

Thorough comprehensive research has been conducted for this project to come up with a good literature review that will help develop a new proposed design system and various materials handling systems were described. Upon developing a new MHS, it is imperative that the following critical aspects are taken into consideration,

- Material Handling Types
- Principles of Material Handling
- Characteristics of Materials
- Machine Stability
- Power Transmission
- Machine Design Research (material selection, Manufacturing process, & Heat treatment).

The new proposed design system is desired to be electro-hydraulically powered, to eliminate the use of MHS that relies on ICE for power source as they pose high risk to OHS of the employees. Therefore, when writing this document's literature review, there was a need to conduct a research on "Exposure to Carbon Monoxide in the Workplace", so that this document can better manage th OHS of the employees. A Hydraulic Power Transmitting System Research was also undertaken, looking deeper in hydraulics principles, functions, advantages and disadvantages, and other concicderations.

CHAPTER THREE

DESIGN DEVELOPMENT OF 3D SOLID MODEL

3. Chapter Overview

The aim of this chapter is to provide a new proposed automated handling equipment design that is to conform with Barloworld Remanufacturing Centre's operation standards and meet ISO, SABS, OHS act standards. Again, the research's technical conceptual designs will be developed and modelled & verified. The design parameters and components of proposed MHS designs consists of a stable robust portable movable structure with a lifting device and/or mechanism.

Design development of conceptual designs, preliminary calculations and selection criterion for each conceptual design are carried out in this chapter considering the different design parameters of a new MHS design validation. This is done to analyse the performance, manufacturing, maintenance, safety of MHS, manoeuvrability, and robustness of proposed MHS with different design parameters. The stability, strength of the structure and accurate selection of materials and lifting mechanism is crucial for safety assurance within the workplace environment and in coming up with a new safe MHS design.

3.6. Design Development Justification

The problem that Barloworld Remanufacturing Centre (BRC) is currently facing is having its dynamometer testing room door and engine department workshop fabric curtain rapid roller door being damaged by a 16-ton forklift truck when travelling from and into the workshop having lifted a 20-cylinder engine on a shipping stand.

A 16-ton forklift damages the Dyno bay door, shaded blue in figure 19, when travelling from BRC warehouse (using yellow routed arrow) going to the engine department to collect fully assembled, tested engines and are ready for dispatch. Engine department workshop door, shaded red in figure 1, gets damaged when a 16-ton forklift has collected ready engines from the holding area inside engine department workshop, shaded green in figure 19, going to the warehouse (using orange routed arrow).

Both doors are being damaged by the forklift due to space availability. The 16-ton forklift currently spans more space than that available, i.e. the forklift's turning radius is not favourable within a 11 m wide travelling passage. Therefore, there is a need to address this problem through emerging technologies and technical innovations by means of designing a system that will have a wheelbase of not more than 2.5 m to achieve much lesser turning radius for good manoeuvrability.

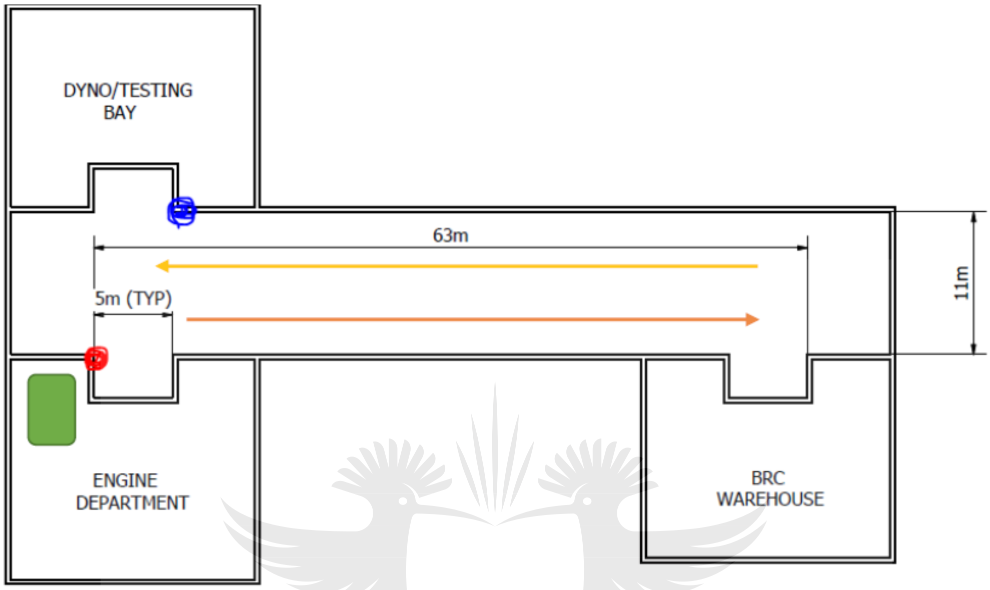


Figure 19 - BRC layout

3.7. Requirements of the Solution

Barloworld Remanufacturing Centre (BRC) strives to deliver effectively and efficiently practical, innovative, knowledge – based solutions addressing material handling and internal logistics. The project aim is to design a portable adjustable system that can lift/lower and transport 20-ton SWL without damaging workshop facilities and posing health risks to workers. Also come up with a power source that will replace the use of ICE, that is using an Electro-Hydraulic system for power source. Thorough research is done on machine stability, hoist mechanism, factors of safety on heavy duty handling systems.

3.7.1. Conceptual Designs Constraints

This section provides an over of measurements take at the BRC workshop and warehouse. These measurements are for the travel path of the existing MHS currently used by BRC, as shown in table 6. Table six also comprises of workshop doors and Engine shipping stands dimensions.

Table 6 - BRC Facility dimensions

BRC travelling passage		**Workshop doors**		**Engine Shipping Stand**		
Width	Height	Width	Height	Width	Breadth	Height
11 m	8.2 m below OH Crane	5 m	6.2 m	2.3 m	4 m	2.5 m

Table 7 - Conceptual Design Performance Table

Load Capacity	**Turning radius**	**Steer Angle**	**Power Source**
SWL 20 ton	< 8 m	146 degrees	Electro-Hydraulics

Table 7 comprises of the proposed system's specification and operating data details.

3.7.2. Conceptual Designs Criterion

To be able to evaluate the concepts effectively, a selection criterion is needed to evaluate and verify each concept. This method takes on the quantitative aspects. The selected criteria are based on the main product characteristics of the problem. From the product specification design, 3 concepts are weighted against each other to determine which one best suit the objective of the problem statement, as shown in table 8.

Table 8 - Conceptual Designs' Selection Criterion Table

Criterion Table and Descriptions	
$Cr1$: **Maintenance**	➢ Maintenance has an impact on the life of the lifting equipment. Easy and safety maintenance procedures are appropriate, as this would encourage personal to practice preventive maintenance. ➢ How expensive repair costs and replacement parts will be. As well as the level of worker and experience needed for maintenance and repair.
$Cr2$: **Usability:**	➢ The machine must be ease of operation, hence user friendly
$Cr3$: **Safety**	➢ Safety refers to the dangers and risks involved with the operation of the machine. This is important to be considered since the machine will require lifting and lowering of heavy loads
$Cr4$: **Mobility**	➢ The purpose of this research is to design a mobile lifting machine. The machine should be easily moved, and a maximum of two people should only be required to complete the movement of the weight lifted.
$Cr5$: **Cost effectiveness**	➢ It is important that cost of material and the machine are considered and are economical.
$Cr6$: **Stability**	➢ The device must be of adequate strength for the proposed of use. An appropriate 'factor of safety' against all foreseeable types of failure, should be used. The position of the load affect stability and center of gravity.
$Cr7$: **Product reliability**	➢ The product life cycle of the product is important. This is necessary as the product will be used daily.
$Cr8$: **Weight of product**	➢ The weight of the product, affect mobility, the weight of the product must be optimized.

NB: The relevant totals of each criteria score, with respect to concepts selected, are added. The concept that generated the most points is chosen for the final concept design.

3.8.Description of Proposed Conceptual Designs

So far, different method has been developed to help understand and define customer needs as clearly as possible. Objective have been set, to further explore and understand the need of the customer. Functional flow structure has been used to address the different functions that needed to be varied out in a flow chart (hierarchical manner) to satisfy those needs and the set objectives. The Product Design Specification (PDS) that must be satisfied was classify above and criteria were measure.

In this section, different concepts are generated and evaluated based on what have been accomplished in the previous sections of the design process. Three different concepts have been generated for this project. These concepts represent multiple solution to the problem defined. Although many designs can be redesigned or modification of existing products. These modifications need to be new and unique.

3.8.1. Conceptual Design 1

Concept 1 is an automated Jib crane like system that is hydraulically driven by two-wheel hubs, each producing power of 80 kW to overcome tractive effort of 136.8 kN. The system is designed to have a counterweight that is to balance working loads during lifting/lowering and transportation. Overall weight and sizes of the system is 39 tonnes, 2.3 m wide and 5.9 m long, turning radius of 8.05 m.

Figure 20 - Concept 1 isometric views

Concept 1 frame structure is made up of 50 mm thick flat plates and the suspension is made up of 50 mm thick solid square tubing to form a strong structure.

Table 9 - Concept 1 List of Materials [28].

List of Materials
➢ FLAT BAR SANS 1431 Grade 350WA, FER PLAT, BARRA RECTANGULAR ➢ Rear and front axles frames are of, 0.5C 080M50, ➢ Lifting beam made up of 305×165×54 (mm×mm×kg/m)

A) Preliminary calculations

Turning radius calculations

Table 10 - Turning radius calculations' Symbols & Abbreviation Descriptions

TR	Turning radius
DW	Door width
MWB	Machine overall width
MOL	Machine overall length
D	Distance between the machine & passage wall
TRR	Turning radius ratio

$$TRR = \frac{(DW - MWB)}{2} \quad \text{.........} \quad (1)$$

$$TRR = \frac{(5 - 3.3)}{2} = 0.85\ mm$$

$$TR = D + (MOL - TRR) \quad \text{.........} \quad (2)$$

$$TR = 3 + (5.9 - 0.85) = \mathbf{8.05m}$$

B) Concept one Advantages and Disadvantages

Advantages

- Easy to operate, require one person to operate.
- The structure provides a lot of stability hence allowing the movement of any load safer consisting of a counter weight to balance the working load.
- The system will consist of a pendant; thus increased safety.

Disadvantages

- Concept 1 is very heavy, totalling to 39 tonnes.
- Consume too much energy due to over weight (will require high powered power source) to overcome tractive effort.
- The concept will come at a cost due to it demanding high power and high strength steel for support.

- Frame made up of fabricated forged 50 mm flat plates. Flat plate does not give high strength and is not applicable for this heavy duty application.
- Cost of 20-ton electric hoist machine is expensive.
- Assembling and dissembling of the equipment consume time.

3.8.2. Conceptual Design 2

Concept 2 is a unique design that also relies on a counterweight coloured blue at the back of the system, as shown in figure 21, to balance the working load. Concept 2 lifting mechanism consists of two hydraulic lifting cylinder that lifts and lower a maroon beam which is attached with an orange spreader beam, as shown in figure 21. The concept is also hydraulically driven and is 2.3 m wide and 5.9 m long, having a turning radius of.

Figure 21 - Concept 2 isometric view

Table 11 - Concept 2 List of Material [28].

List of Materials & Manufacturing process
➢ Body frame made up of BS EN10025 / S355 JRA, Hot rolled
➢ Rear and front axles frames are of, 0.5C 080M50,
➢ Lifting beam made up of 305×165×54 (mm×mm×kg/m) I-section, UNIVERSAL BEAMS SANS 1431 Grade 350WA, H.E.A. S275JR, FERRO I

A) *Preliminary calculations*

Turning Radius Calculations

$TRR = \frac{(DW-MWB)}{2}$ .... (1)

$$TRR = \frac{(5-3.3)}{2} = 0.85\,mm$$

$TR = D + (MOL - TRR)$ .... (2)

$TR = 3 + (5.7 - 0.85) = \mathbf{7.85\ m}$

B) Bending Stress Calculations, Data & Abbreviation descriptions.

Table 12 - Bending Stress Calculation Symbols & Abbreviation descriptions.

$\boldsymbol{P}$	*Applied load*
$\boldsymbol{m}$	*Mass of the object*
$\boldsymbol{g}$	*Gravitaional acceleration*
$\boldsymbol{R_{A\&B}}$	*Reactions*
$\boldsymbol{\theta_{bending}}$	*Bending Stress*
$\boldsymbol{BM}$	*Bending Moment*
$\boldsymbol{\bar{y}}$	*Vertical Distance away from the nuetral axis*
$\boldsymbol{I}$	*Moment of Inertia around the nuetral axis*

C) Calculating load applied to the H-section beam,

P=mg

P=20 000 ×9.81= 196.2 kN

RA= RA= 1962002/= 98100 N

Therefore, bending stress

$\theta_{bending} = \frac{BM\times\bar{y}}{I}$ .... *(3)*

Calculation data

$$\bar{y} = \frac{305}{2} = 152.5\ mm$$

$$I = 125 \times 10^{-6}\ mm^4$$

$$\theta_{bending} = \frac{142245 \times 0.1825}{125 \times 10^{-6}} = 193.539\ MPa$$

D) Concept one Advantages and Disadvantages

Advantages

- Easy to operate, require one person to operate.
- The structure provides a lot of stability hence allowing the movement of any load safer consisting of a counter weight to balance the working load.
- The overall size and turning radius of the concept falls within space availability spec, thus gives the machine good manoeuvrability and flexibility.
- The system will consist of a pendant; thus increased safety.

Disadvantages

- Concept 2 is very heavy, totalling to 39 tonnes.
- Consume too much energy due to over weight (will require high powered power source) to overcome tractive effort.
- The concept will come at a cost due to it demanding high power and high strength steel for support.
- Frame made up of fabricated forged 50 mm flat plates. Flat plate does not give high strength and is not applicable for this heavy duty application.
- Cost of 20-ton electric hoist machine is expensive.
- Assembling and dissembling of the equipment consume time and will require specialised tools for the process.

3.8.3. Conceptual Design 3

Referring to Figure 22, the system consists of table like structure made up of bolt connected 305×305×158 mm Standard Parallel Flange H-section steel to form a strong robust frame. The standard H-section steel was chosen for its high UTS (ultimate tensile stress) so that the frame can withstand critical heavy loads. The system also includes a hydraulic power circuit system whereby four hydraulic wheel hubs are used for propelling the system, a hydraulic steering cylinder for steering front wheels and four heavy duty hydraulic lifting cylinder for lifting and lowering the load. Lastly, electronical, and electrical controls system is used for controlling the functionality of the system. The overall system is designed in such a way that it can facilitate ease of maintenance and has a safe operation of loading and unloading which is done with a pushbutton pendant controller.

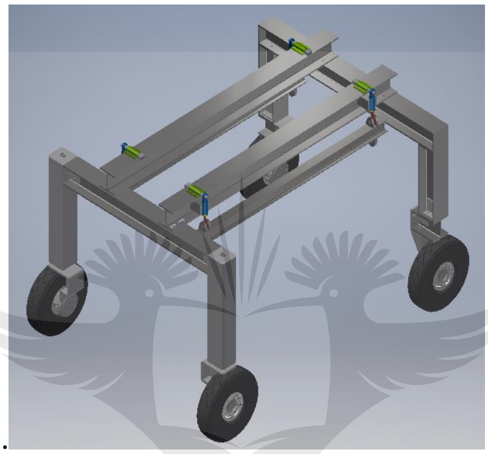


Figure 22 - Automated Heavy-Duty Handling system

A) *Preliminary calculations*

Turning radius calculations

$TRR = \frac{(DW-MWB)}{2}$ (as shown in equation 1)

$$TRR = \frac{(5-4.9)}{2} = 0.05\ mm$$

$TR = D + (MOL - TRR)$ (as shown in equation 2)

$$TR = 3 + (4.9 - 0.05) = \mathbf{7.85\ m}$$

B) *Calculating load applied to the H-section beam.*

Please as shown in table 12 for Bending stress calculations' symbol and abbreviation descriptions. Therefore,

$P{=}mg$

$P{=}20\ 000 \times 9.81{=}\ 196.2\ kN$

$RA{=}\ RA{=}\ 196200/2{=}\ 98100\ N$

Therefore, bending stress

$\theta_{bending} = \frac{BM \times \bar{y}}{I}$ *(as shown in equation 3)*

$$\bar{y} = \frac{305}{2} = 152.5\ mm$$

$$I = 125 \times 10^{-6}\ mm^4$$

$$\theta_{bending} = \frac{142245 \times 0.1525}{125 \times 10^{-6}} = 173.539\ MPa$$

C) *Calculating Factor of safety experienced by the H-section beam*

$\boldsymbol{d}$: $distance$

$\boldsymbol{n}$: $Factor\ of\ safety$

NB: For use with highly reliable materials where loading and environmental conditions are not severe and where weight is an important consideration.

Factor of Safety – FOS (as shown in chapter 6 simulation results, equation 19 and Table 40)

$BM = P \times d$ .... (4)

d = 2.9/2

P = 98100 N

BM = 98100×1.45 = 142245 $N.m$

D) *Preliminary Tractive effort calculations (power supply selection) for concept 3.*

Determining power required to overcome tractive effort for concept 3.

Table 13 - Tractive effort calculation' symbol & abbreviation descriptions.

$\boldsymbol{TE}$	$Tractive\ effort$
$\boldsymbol{P_{engine}}$	$Engine\ power$
$\boldsymbol{F}$	$Axial\ load$
$\boldsymbol{\mu}$	$Friction\ coefficient$
$\boldsymbol{v}$	$Linear\ velocity$

Therefore,

Table 14 - Traction Coefficients for normal Vehicle Tires [29].

Surface	Traction Coefficient - μ_t -
Wet Ice	0.1
Dry Ice/Snow	0.2
Loose Sand	0.3 - 0.4
Dry Clay	0.5 - 0.6
Wet rolled Gravel	0.3 - 0.5
Dry rolled Gravel	0.6 - 0.7
Wet Asphalt	0.6
Wet Concrete	0.6
Dry Asphalt	0.9
Dry Concrete	0.9

$$F = \mu(m.g) \quad \ldots\ldots\ldots \quad (5)$$

$$F = 0.8\ (2000 \times 9.81) = 137340\ N$$

$$F = \frac{156960}{4} = 39240\ N$$

Expected travelling speed, **5 km/hr**

$$P_{engine} = F.v$$

$$P_{engine} = 39240 \times \frac{5}{3.6} = 54.5\ kW$$

Each wheel requires 54.5 kW to overcome $\boldsymbol{TE}$, overall power required is 218 kW.

E) Concept one Advantages and Disadvantages

Advantages

- Easy to operate, require one person to operate.
- The structure provides a lot of stability hence allowing the movement of any load safer consisting of a counterweight to balance the working load.
- From above mentioned overall sizes and turning radius of the concept falls within space availability spec, thus gives the machine good manoeuvrability and flexibility.
- The system will consist of a pendant, thus increased safety.
- H-section steel is a high strength material with ultimate yield strength of 710 MPa, frame is reliable.
- Hub bracket are made up of high strength material, make the component reliable.
- Hydraulic power pack is much cheaper than electrical components

Disadvantages

- High strength materials are expensive.
- Hoisting mechanism used for the design is also expensive
- Hydraulics may promote bad housekeeping when there's spillage.

3.5. Concept Evaluation/ Final Selection of best concept

This section covers the final selection process of choosing the best design suitable for meeting the requirements of the problem statement. This is done by using the ranking criteria, as shown in table 15 & 16.

3.5.1. Ranking criteria

Table 15 - Selection Criteria Key points

Bad	Mediocre	Good	Excellent
1	3	6	9

Table 16 - Concept Comparison table or Ranking Criteria

Criteria	Concept 1	Concept 2	Concept 3
Maintenance	3	6	9
Usability	6	6	9
Safety	3	3	6
Mobility	9	9	9
Cost effectiveness	3	3	9
Product liability	6	6	9
Weight of product	3	3	3
Manoeuvrability	6	6	9
Total points per concept	**39**	**42**	**63**

Comparison Table 15 & 16 were used for concept evaluation & ranking criteria in support of the final selection of the best conceptual design.

3.6. Choice of best Conceptual Design Summary

Concept three has been chosen to be the final design for this project as it scored highest, as shown in table 16. It consists of a table like frame that has a hoisting mechanism mounted on its top surface at the middle of the body. The hoisting mechanism consists of a spreader beam made up of I-section steel and is inter-connected with 4 lifting hydraulic cylinders attached to the two I-section steels located at the top section on the main structure. The frame is made up of a combination of 305×305 H-section, 4 fabricated Hub brackets which are mounted on the bottom section of the frame. 4 hydraulic wheel hubs will be bolt mounted on the fabricated Hub brackets. The system also operates with close loop hydraulic power pack that supplies hydraulic energy to the steering cylinder and 4 hydraulic motors and lifting cylinders. Bearings are selected in accordance with rolling elements applications. The overall system width, height and length are 2.9 m, 3.91 m, respectively. The final design selection consists of three main critical components that are designed and need to be evaluated, and are as follows,

- Hub bracket - experiences too much of buckling and bending force due to having to withstand 20 – ton uniformly distributed per leg.
- Hydraulic Steering Cylinder Bracket – this component experiences too much of torsional stress since it needs to overcome friction under load when turning.
- Steering cylinder shaft also experiences too much of torsional stress.
- Bolt connection of the main structure is evaluated to verify the factor of safety and the deflection of beams when the system is under load.

CHAPTER FOUR

PERFORMANCE ANALYSIS OF THE NEW SYSTEM

4.1. Chapter Overview

The aim of this chapter is to model and analyze the performance of the final design chosen for this project research. The design parameters of the selected concept, thus for the new system includes, calculation & verification of Vehicle Dynamics of the new system, Stress Analysis of the main structure and hoisting mechanism, and Hydraulic Power pack validation in terms verifying operating pressures for the hydraulic system. Calculations of the new model were carried out in this chapter considering the different varying design parameters (Mainly SWL & Frame structure material) of the new system. The specification of the new design system should be accurate to achieve the correct results and/or outcomes for safe operation and proper handling of goods in the workplace.

4.2. Technical Calculations of the New System Design

This section focuses on verifying and validating the new system's stability, and performance. Whereby the overall system, based on material and components selected to form the new design, must be able to lift, lower and be able to move even when under maximum load. Therefore, engineering principles, laws and equation are carried out is achieving

4.2.1. Vehicle Dynamics Approach

This section provides analysis and study of how the new system will react to driver inputs on a given road or surface condition. Vehicle motions are largely due to the shear forces generated between the tires and road, and therefore the tire model is an essential part of the mathematical model. In this paper the tire model will be analyzed to produce realistic shear forces during braking, acceleration, cornering, and combinations, on a range of surface conditions. As shown in figure 23.

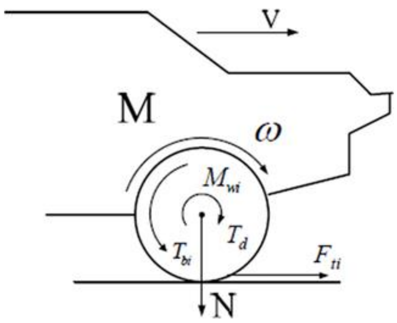


Figure 23 - Quarter model of vehicle expressing wheel and body dynamics [30].

When selecting drive wheel motors for mobile vehicles, several vehicle dynamics factors are considered to determine the maximum torque required to move the vehicle. To choose motors capable of producing enough torque to propel the new proposed system, it is necessary to determine the total tractive effort (TTE) requirement for the vehicle:

TTE [N] = RR [N] + Fa [N] …………………………………………………………………… (6)

The components of this equation will be determined in the following steps below.

4.2.2. Determining Rolling Resistance

Rolling Resistance (RR) is the force necessary to propel a vehicle over a surface. The worst possible surface type to be encountered by the vehicle will be factored into the equation.

RR[N] = W_GV [N]+μ ………………………………………………………………... (7)

Therefore:

Considering worst possible surface type and maximum load capacity condition to achieve RR of the new system.

W_GV = 30000×9.81 = **294.3 kN** ; μ=0.71 (as shown in table 13)

RR = 294300×0.71 = **208.953 kN**

4.2.3. Determining Acceleration Force

Acceleration Force (Fa) is the force necessary to accelerate from a stop to maximum speed in a desired time.

$$Fa = \frac{W_{GV} \times V_{max}}{g \times t_a} \quad \text{……………………………………………………………………..} \quad (8)$$

Calculation data.

Considering, $t_a = 1s$; $V_{max} = 5\frac{km}{hr}$ $(walking\ speed)$; $g = 9.81[\frac{m}{s^2}]$

$W_{GV} = 294{,}3\ kN$ to achieve Fa of the new system.

$$Fa = \frac{294{,}3 \times {}^{5}/_{3600}}{9.81 \times 1} = \mathbf{41.67\ kN}$$

4.2.4. Determining Total Tractive Effort

The Total Tractive Effort (TTE) is the sum of the forces calculated in 4.2.2 and 4.2.3.

Therefore: TTE[N]=RR [N]+Fa[N] (as shown in equation 6)

TTE = 208,953+41.67 = **250.623 kN**

4.2.5. Determining Hydraulic Wheel Motor Torque

To verify if the new proposed system will perform as designed with regards to tractive effort and acceleration, it is necessary to calculate the required wheel torque (T_w) based on the tractive effort.

$$T_w = TTE \times R_w \times R_f \quad \text{.......} \quad (9)$$

The resistance factor accounts for the frictional losses between the solid pneumatic tires and the drag on their hydraulic drive hub gear system and bearings. Typical values range between 1.1 and 1.15 (or 10 to 15%) [4].

Considering, $R_f = 1.1$; $R_w = 0.541\ m$; $TTE = 250.623\ [N]$

$$T_w = 250.623 \times 0.541 \times 1.1 = 149.1\ kN.m$$

4.3. Determining Bending Moments of System Frame Structure

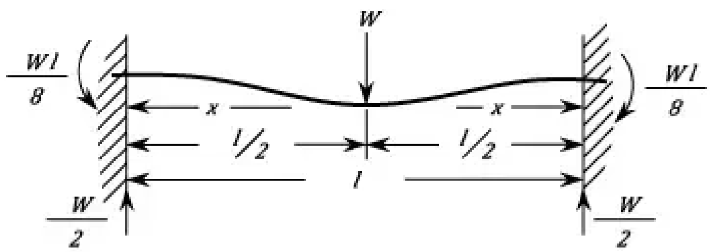


Figure 24 - Fixed End Moments structure diagram [31].

Please note, only a quarter of the system will be analyzed because each quarter exert the same force as 20 ton of load is uniformly distributed. Therefore,

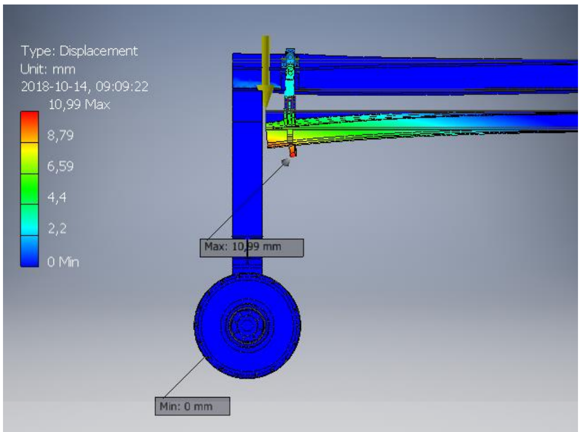


Figure 25 - New system Quarter Section illustration under load

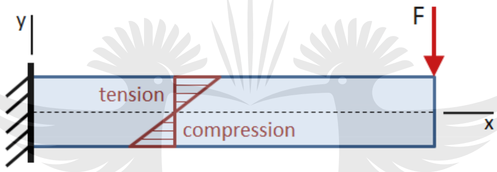


Figure 26 - Cantilever Free body diagram [32].

Bending stress of the spreader beam.

$\sigma = \frac{BM}{I_x}$ (as shown in equation 3)

σ = (49.05×0.3× 〖10〗 ^3)/(47.8× 〖10〗 ^(-6)) = **307.845 MPa (safe)**

SABS 1431 EN10025 Standard H-sectioned steel, Ultimate Tensile Stress 480 – 650 MPa, Yield strength 340-350 MPa, BHN Hardness average 140, with good LH practice weldability. Safety Factor, n= 650/307.845 = 2.11, good safety factor for heavy duty handling.

4.4. Shear Stress for H-Section Beam

The Shearing Force at any cross section of a Beam will set up a Shear Strain on transverse sections which in general will vary across the section.

In the following analysis it has been assumed that the Stress is uniform cross the width (i.e. parallel to the neutral axis) and that the presence of shear stress does not affect the distribution of Bending Stress. Due to the Shear Stress on transverse planes there will be complementary planes parallel to the neutral axis [4].

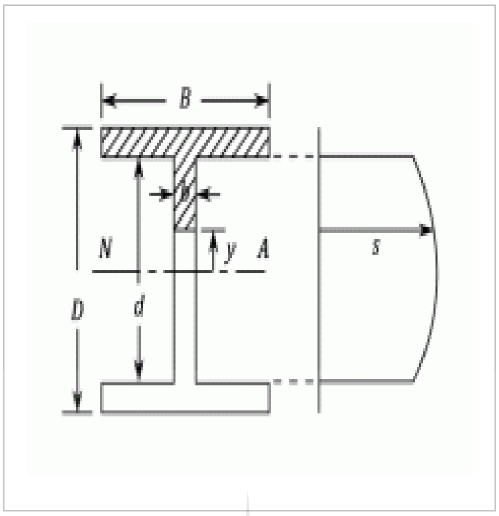


Figure 27 - Standard steel section shear distribution diagram [32].

V: Shear Force

I_x: Moment of Inertia

I: Second area moment of the cross-section

B: Thickness of the material

Shear Stress calculation data.

The shear stress from A-A: $\tau_A = 0$, (A=0)

$V = 6000x9.81$

$V = 58.86kN$

$I_x = 195x10^{-6}m^4$

$$\bar{y}_{max} = \frac{356}{2} = 178\text{mm (from botom)}$$

$$\tau_{max} = \frac{VA\bar{y}}{IB}$$

The shear stress from B-B:

$\tau_B = \frac{VA\bar{y}}{Ib}$ ………………………………………………………………………………… (10)

$$\tau_B = \frac{(58.86x10^3)(9.1x10^{-3}x0.171)(0.178 - \frac{0.0091}{2})}{(195x10^{-6})(0.171)}$$

$\tau_B = 2.786\text{MPa}$

The shear stress at the Neutral Axis:

$$\tau_{N.A} = \frac{VA\bar{y}}{Ib}$$

$$\bar{y} = (9.1x10^{-3}x0.171)\left(0.178 - \frac{0.00091}{2}\right) + (0.1689)(0.0157)(0.08445)$$

$\bar{y} = 4.94x10^{-4}\text{m}$

$$\tau_{N.A} = \frac{(58.86x10^3)(4.94x10^{-4})(9.1x10^{-3})}{(0.0157)(195x10^{-6})}$$

$\tau_B = 9.498\text{MPa}$ (***Safe for load type application)***

The maximum value of shear stress occurs at the neutral axis ($y_1 = 0$), and the minimum value of shear stress in the web occurs at the outer fibres of the web where it intersects the flanges

$y_1 = \frac{\pm h_w}{2}$: ………………………………………………………………………………… (11)

Showing that the Shear Stress in the flanges varies from a maximum at the top web to zero at the outer tips.

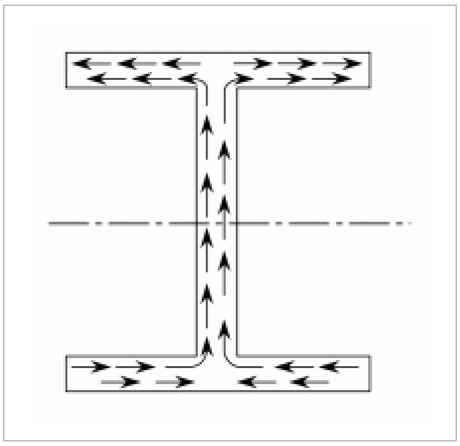


Figure 28 - H-beam stress distribution illustration [32].

The maximum deflection of this cantilever beam with end point load is found @ x=L and the maximum speed is found when the load @ x=L The distribution of shear stress along the web of an H-Beam is shown in figure 28 & 29:

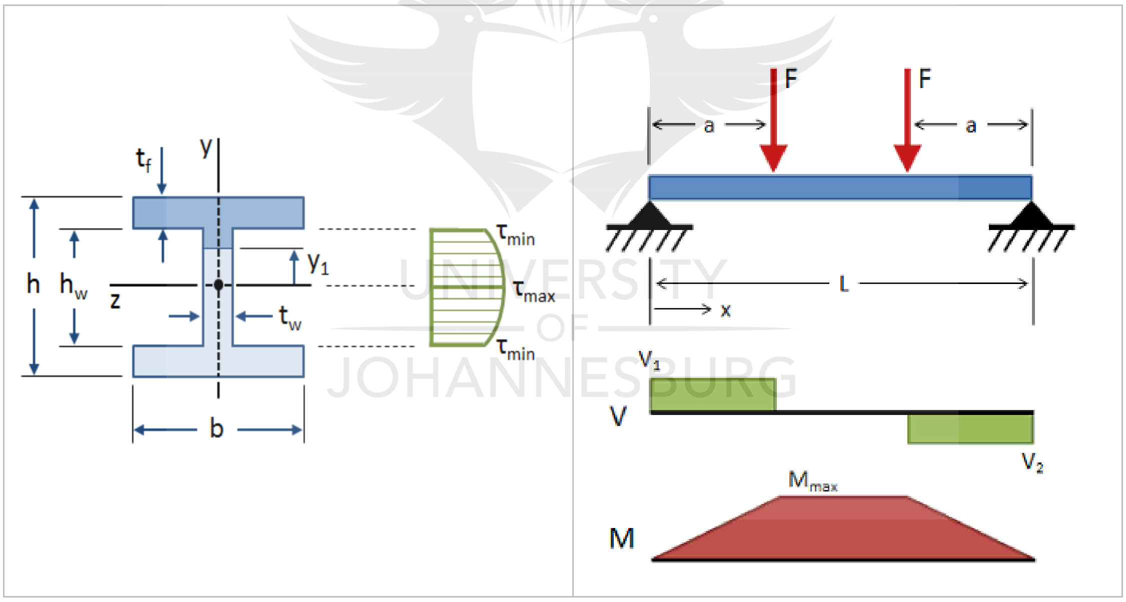


Figure 29 - Shear and Bending stress illustration on system structure [32].

4.5. Inside and Outside Steering Angle of the New Design System

The requirement for our vehicle is to keep turning radius low, so the outside turning radius of our vehicle was found to be 7.85 meters through vehicle dynamics technical calculations, as shown in 3.3.3.

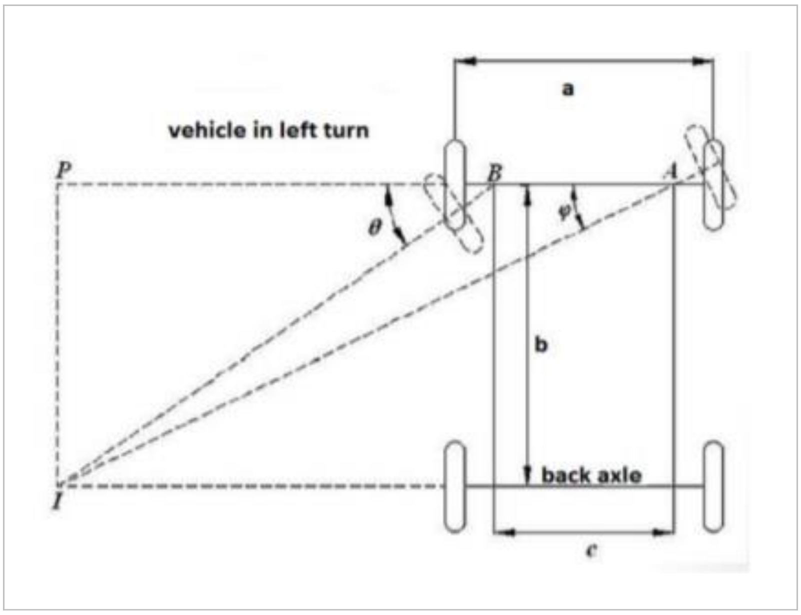


Figure 29 - Vehicle in turn IA is turning radius [33]

Therefore, Inside and Outside Steering Angle equation and calculation are as follows,

$R = \frac{b}{\sin\theta} + \frac{a-c}{2}$ [33]……………………………………………………………….…….. (12)

(by geometry in Figure 29) in relation to a, b & c values that are dimensions of the new design system from figure 43 & 44, as shown in 6.2.3.

$7850 = \frac{4450}{\sin\theta} + \frac{3950-2730}{2}$,

$\theta = \sin^{-1}(0.614)$

$\theta = 37.93°$

Now by correct steering geometry,

$\cot\theta - \cot\varphi = \frac{c}{b}$ [33]………………………………………………………………… (13)

$\cot 37.93° - \cot\varphi = \frac{2730}{4450}$

$\varphi = \cot^{-1}(\cot 37.93° - \frac{2730}{4450})$

$\varphi = 56.2°$

Total steering angle = 37.93 + 56.2 = 94.13°

4.6. Determination of Steering Effort of the New Design System

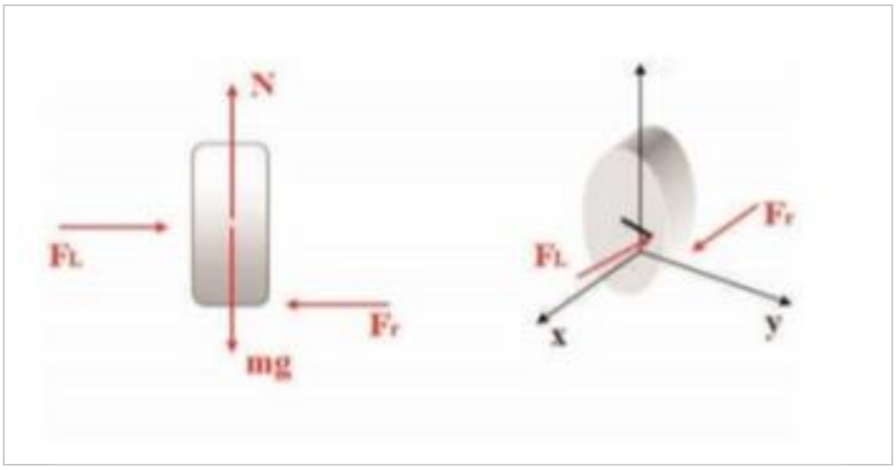


Figure 30 - Forces acting on wheel [33]

Referring to figure 31, forces acting on wheel variables' data description.

$\boldsymbol{mg}$: $Weight$

$\boldsymbol{F_L}$: $Lateral\ force$

$\boldsymbol{F_r}$: $Friction\ force$

N: $Normal\ force$

Steering effort is defined as the effort to be made by the driver or operator of a vehicle in turning the steering wheel. This can be calculated in either static condition i.e. when the vehicle is stationary and in dynamic conditions. Steering effort is maximum when the vehicle is stationary and the forces in all direction are in equilibrium [33].

W_GV = 30000×9.81 = **294,3 kN** (as shown in 4.2.2)

RA= RA= $1962002/$= **98100** N (as shown in 3.3.3)

Reaction at each tire = $(RA/2\ +\ mass\ of\ tire) * 9.81$ [33]………………………….. (14)

$= 98100/2 + 13.14 * 9.81$

$= \mathbf{481.31}\ kN$

The tires used for the vehicle are mud tires and coefficient of friction between tires and rolled gravel ground is 0.6 (data provided by various tire manufacturers), as shown in table 14.

The friction force at the tire is $= \mu * Reaction\ force\ at\ each\ tire$ ………………… (15)

$$= 0.6 * 481.31 \times 10^3$$

$$= \mathbf{288.786}\ kN$$

While turning the steering wheel the torque will transmit to steering clamp bracket and then to the split joint shaft and this torque should be equal or greater than the frictional resistance of the ground to be able to turn the tire. From this, the value of steering arm torque is calculated by multiplying length of steering clamp bracket (460mm) with the friction force FR.

Steering Clamp Bracket (SCB) torque = $288.786 \times 10^3 \times 0.460$ = **132.84** kN-m

The amount of force or effort required on the steering wheel is calculated by dividing the torque by the radius of steering wheel (R = 945/2 mm).

Therefore,

$$Steering\ effort = 132.84/\ (0.477)$$

$$Steering\ effort = \mathbf{278.49}\ kN$$

The amount of steering bending moment required on the steering clamp support bracket is calculated by multiplying the steering effort by the distance of the steering clamp bracket.

Therefore, steering clamp support bracket distance = 460 mm

$$Steering\ Bending\ Moment = 278.49 \times 0.46$$

$$= \mathbf{128.1}\ kN.m$$

4.6.1. Required Angle at the time of Maximum Turn

Table 17 - Required Internal Wheel Steer Angle at sharp corners [33].

Velocity (m/s)	FYF (N)	Slip Angle (degree)	Required angle (degrees)
0	0	0	0
1.39	67.23	0.16	54
2.78	268.9	0.7	53.4
4.167	602.2	1.5	52.67
5.55	1071.9	2.7	51.47
6.94	1700	3.96	50.21

Above table shows, that at the time of sharp cornering the vehicle is oversteering i.e. the rear tires lose their traction before front tires and slip angles are induced and required angle for maximum turning reduces because the vehicle is steering more than the operator or the driver's feed at the steering wheel [33].

4.7. Design of the Hydraulic System of Working Device in the New Design System

4.7.1. Design Overview of the Hydraulic System

The new design system' hydraulic system includes four lifting hydraulic cylinders and steering hydraulic cylinder. The lifting hydraulic cylinder can lift the goods. The Spreader Beam attached to lifting cylinders can make before and after loading framework, to facilitate handling and walking, and easy to use [34].

The hydraulic pump' output operational pressure creates hydraulic fluid flow into the working device and steering mechanism, respectively. A hydraulic system is an important power source of the working process of the new system design. A reasonable hydraulic system scheme can meet most requirements of various functions, and convenient manipulation, reliable operation, smooth motion, convenient adjustment, and maintenance of the new design system [34].

4.7.2. Principles of the Hydraulic System

Design description of the hydraulic power pack system:

- Hydraulic Tank,
- Hydraulic pump: the gear pump has been adopted as working oil pump,
- Working motor,
- Lifting oil cylinder: Double-acting hydraulic cylinder,
- Adjustable Hydraulic Steering Cylinder,
- Hydraulic control valve: multiple directional control valves,
- The speed limit flow control: a one-way valve,
- Auxiliary hydraulic parts design: design of filter, air filter design, various kinds of instrument choice selection of seal, hydraulic oil, and pressure loss calculation.

Detailed principles and diagrams of hydraulic power pack system has been shown and explained in Chapter 7.

A) Maximum Working Pressure and Flow Rate of the Lifting Oil Cylinder

The working pressure is 100 kg/cm^2 & the flow rate is 50 L/min for the system, thus normal pressure and flow rate for hydraulic heavy duty lifting systems [38].

B) Maximum Pressure of the Hydraulic System

Maximum pressure of the reversing valve requirement is 140 kg/cm^2, with reference to the similar products, P_1 has been chosen to be 100 kg/cm^2.

4.7.3. Pump Power Capacity Analysis

Pump drive power validation,

$P = \frac{P_p + Q_n}{61.2 \times \mu_v}$ [34] …………………………………………………………………… (16)

In the formula, P_p is the actual maximum working pressure of the pump, of 140 MPa; Q_n is the rated flow of pump and the operating value is 510 m^3/s; μ_v is the mechanical efficiency of the pump of 0.8.

So, $P = \frac{140\times10^{6}+510\times10^{-6}}{61.2\times0.8}$

$P = \mathbf{1458.33}\ W$

4.7.4. Pump Motor Selection

Pump motor selection is conducted in accordance with the hydraulic pump rated speed and power needed to drive and deliver the rated flow rate. The Z4-112-4 electric motor has been selected and its parameters are as follows.

Table 18 - Pump Motor Specifications

Rated power	5.5 kW
Rated voltage	160 V
Rated current	42.7 A
Speed (highest)	3000/4000 r/min
Efficiency	83.5%
Flywheel moment	0.8

So, pump motor' rated power calculation in relation to hydraulic pump power

$P = 1458.33\sqrt{\frac{15}{5}} = \mathbf{2525.9}\ W$, motor capable to run the hydraulic power pack system pump.

4.7.5. Design Calculation of the Tubing or Pipeline of the Hydraulic Power Pack System

Pressure & diameter of hydraulic power pack pipeline analysis:

$Q = \frac{\pi}{4}\times d^{2}\times v$ [34] ………………………………………………………………… (17)

Calculation data

$Q = 300\ L/min\ ;\ v = 0.6\ m/s$

Therefore,

$$d = \sqrt{\frac{4 \times 300}{0.6 \times \pi}} = \mathbf{25.23}\ mm$$

Verifying the hydraulic system design manual, in accordance to the oil mouth nominal or fitting diameter size: d = 25 mm, outside diameter is 32 mm & the corresponding pipe fitting thread is M32×1.5 [34].

4.7.6. Velocity inside Hydraulic Tubing

$$V = \frac{4Q}{\pi d^2} \quad [34] \quad \ldots\ldots\ldots\ldots \quad (17)$$

4.7.7. Wall Thickness of the Pipe Tubing

$$\delta = \frac{Pd}{2\,[\sigma]} \quad [34] \quad \ldots\ldots\ldots\ldots \quad (18)$$

$$\delta = \frac{2100 \times 50}{2\,[1500]}$$

$$\delta = \mathbf{3.5}\ mm$$

The outside diameter of steel pipe tubing = $25 + 2 \times 3.5 = \mathbf{32}\ mm$

4.8. Fillet Weld Design

A flat-faced, equal-legged fillet weld in a 90° T-joint has a theoretical throat dimension of 0.707 ω, where ω is the leg size. When the welding process and procedure achieve a depth of penetration beyond the root, then the effective throat dimension is increased for fillet welds with equal leg sizes [36].

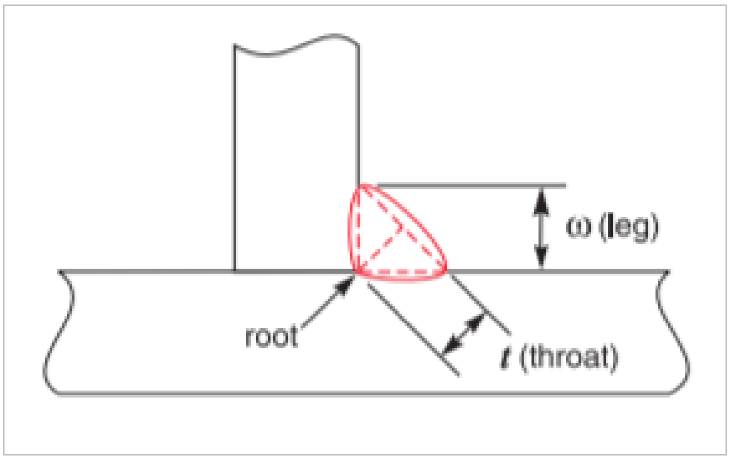


Figure 31 - Convex fillet weld

4.8.2. Convex fillet weld – is a fillet weld in which the contour of the weld metal lies outside a straight line joining the toes of the weld. A convex fillet weld of specified leg length has a throat thickness more than the effective measurement [35].

Table 19 - Afrox Fillet and Weld Data [35]

Nominal Fillet Size (mm)	Min. Throat Thickness (mm)	Plate Thickness (mm)	Electrode Size (mm)
5,0	3,5	5,0 – 6,3	3,2
6,3	4,5	6,3 – 12,0	4,0
8,0	5,5	8,0 – 12,0 and over	5,0
10,0	7,0	10,0 and over	4,0

4.8.3. Front and Rear Wheel Hub Support Brackets weld summary

The new system design's hub support bracket materials have been chosen to be 40 mm thick plates. Available Carbon Steel plates available from the market ranges from 16 - 40 mm in thickness, therefore, for the design of hub bracket, thickest steel plate were chosen for over design purposes since the new system will be operating under heavy loads (20 – ton). Simulations of fabricated 40 mm thick steel plates will be simulated and evaluated in chapter 6.

Referring to table 19, fabricated rear and front wheel hub support brackets have a Nominal fillet Size of 10.0 mm & Throat Thickness of 7.0 mm.

CHAPTER FIVE

MATERIAL SELECTION FOR NEW SYSTEM DESIGN

5. Chapter Overview

This section covers the selection of materials and components to be used in the manufacture and assembly of the new system. Legislation covering lifting machinery, Electrical Machinery, Pressure Equipment Regulations, Environmental Regulations for workplace, ISO (international Organization for Standardization), and SABS (South African Bureau of Standards) are very strict when coming to materials & component selection and the process of manufacture and they need to be adhered to. Therefore, specification of the new system and material selection should be accurate in order to achieve correct results and that the new system may be able to perform at its design capacity and meeting engineering legislation standards and codes as well as achieving heavy duty material handling principles.

5.1. Manufacturing Process for considered Model

This section provides detailed overview for manufacturing process and material selection of the new system's components. Critical components will be discussed and assessed, and are namely, Hub Bracket (Rear fixed & Front swivel), Main Frame Structure, Split Flange Joint Shaft, Spreader Beam and Steering Clamp bracket.

5.2. Materials Selection Justification

350WA SANS 1431, SANS 50025 / EN 10025 Grade S355JR and ASTM A36 are the most used mild and hot-rolled steel. Both materials have excellent welding properties and is suitable for grinding, punching, tapping, drilling, and machining processes. Yield strength of ASTM A36 is less than that of cold roll C1018, thus enabling ASTM A36 to bend more readily than C1018. Normally, larger diameters in ASTM A36 are not produced since C1018 hot roll rounds are used.

350WA SANS 1431, SANS 50025 / EN 10025 Grade S355JR and ASTM A36 material are usually available in the following forms:

- Rectangle bar.
- Square bar.
- Circular rod.
- Steel shapes such as channels, angles, H-beams, and I-beams.
- Wear Plate (Hard Wearing Plates).

The criteria below are employed for best selection of materials and components.

Table 18 – Material Selection ranking criterion

CR1	Machinability
CR2	Wear resistance and good toughness
CR3	Corrosion resistance
CR4	Good combination of strength and ductility
CR5	Moderate hardness
CR5	Cost effective

5.3. Main Frame Structure Manufacturing Process & Material Selection Description

The H-section & I-section are a standard steel and are considered for the construction of the new system main frame structure design. As described in chapter 3, the main frame structure takes a form of a table structure, where it consist of or is built up of a combination of H-section steel, Hollow square tubes and I-section steels all joined together using bolt connection method.

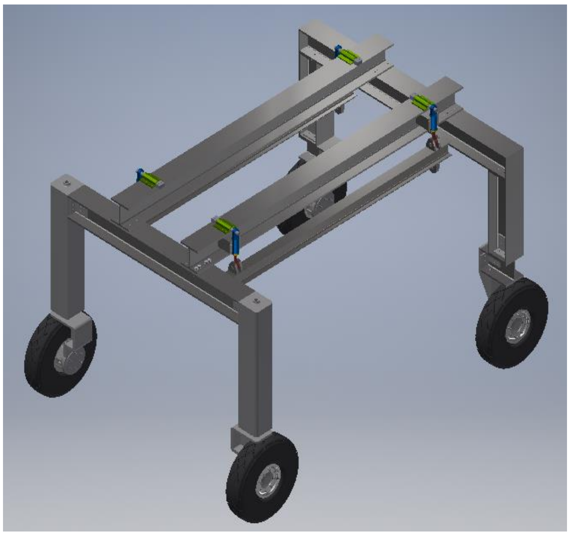


Figure 32 - Main Frame Structure

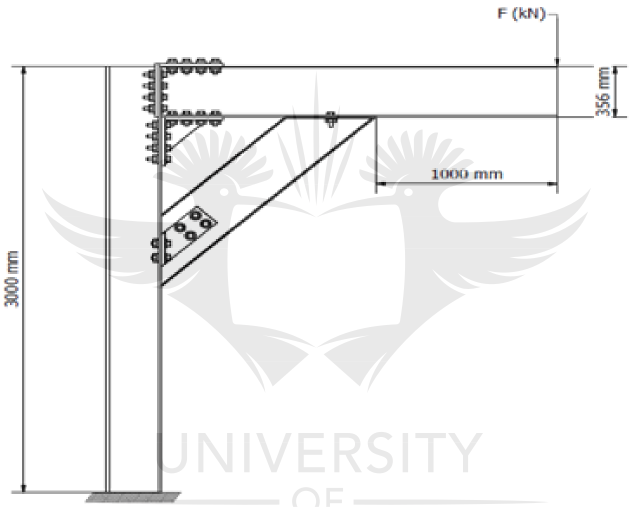


Figure 33 - Bolt Connection Illustration (Quarter of Main Frame)

General H-section & I-Section steel selection criteria would typically include:

- Deflection limits, according to the specified standard on vertical and lateral deflections of the structure for the purpose of obtaining satisfactory hoisting service performance.
- Vertical deflection due to the maximum wheel loads and level supports. High impact resistance, high fatigue life for the chosen material.
- The beam must support a 20 ton and must be capable of withstanding contact stresses between beam to beam connection and bracket to beam.

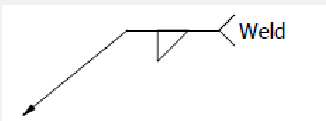
Section steels comes in standard length; only a cutting torch and very large grinding equipment are used to cut the steel to desired length and for creation of holes for bolts slots. Main frame structure consists of,

- Four 305×305×158 (**mm×mm×kg/m**) H-Section, Universal Columns SANS 50025 / EN 10025 Grade S355JR, drilled on both ends with 25 mm diameter holes for bolt slots.
- Two 305×165×54 (**mm×mm×kg/m**) I-section, Universal Beams SANS 50025 / EN 10025 S355JR, for spreader beam support. Also drilled on both ends with 25 mm diameter holes for bolt slots.
- Two 285 x 285 mm×mm Square Tubing (Hot Rolled).
- Four 40 mm thick wearplates of (W200) - SS10/200 [Hard Wearing Plate (Bennox)], attached through weld (Fillet size of 10 mm & throat size of 7 mm) on both ends of two Square Tubing, having 60 mm diameter bore at the center for Split joint shaft slots. Main Frame metrial's yield stress is 760 Mpa.

5.4. Front and Rear Wheel Hub Support Brackets Manufacturing Process & Material Selection Description.

Front & Rear hub support brackets are constructed using fabrication manufacturing method. Hub support brackets are made up of a combination of 40 mm thick plates and 20 mm thick plates to form a strong support structure, i.e. supporting the main frame and wheel hubs, thus joining them together to form a supported movable structure. Hub support brackets consist of five 40 mm thick and two 20 mm thick plates joined by means of welding method. Hub support brackets are used to attach and support hydraulic wheel hubs to the main frame structure.

Table 20 - Plates (Commercial Quality, S355 JR / JO and Vastrap Plates) data [28].

Properties by **SANS 1431** Weldable Structural Steel Plate	
Thickness	16 - 40 mm.
Yield Strength	760 MPa
Tensile Strength	480 - 650 MPa
Elongation	> 18 %
Weld Symbol	

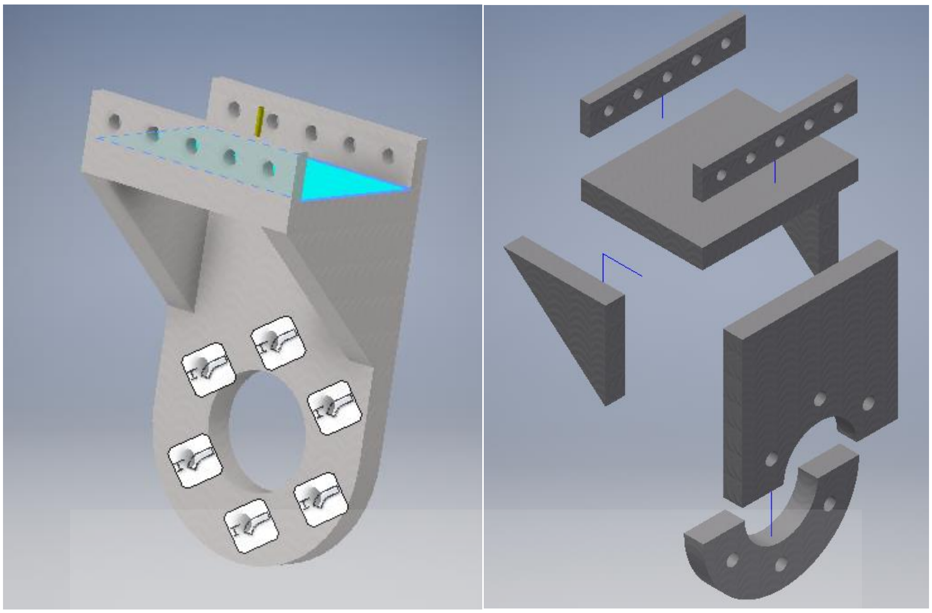


Figure 34 - Hub Support bracket

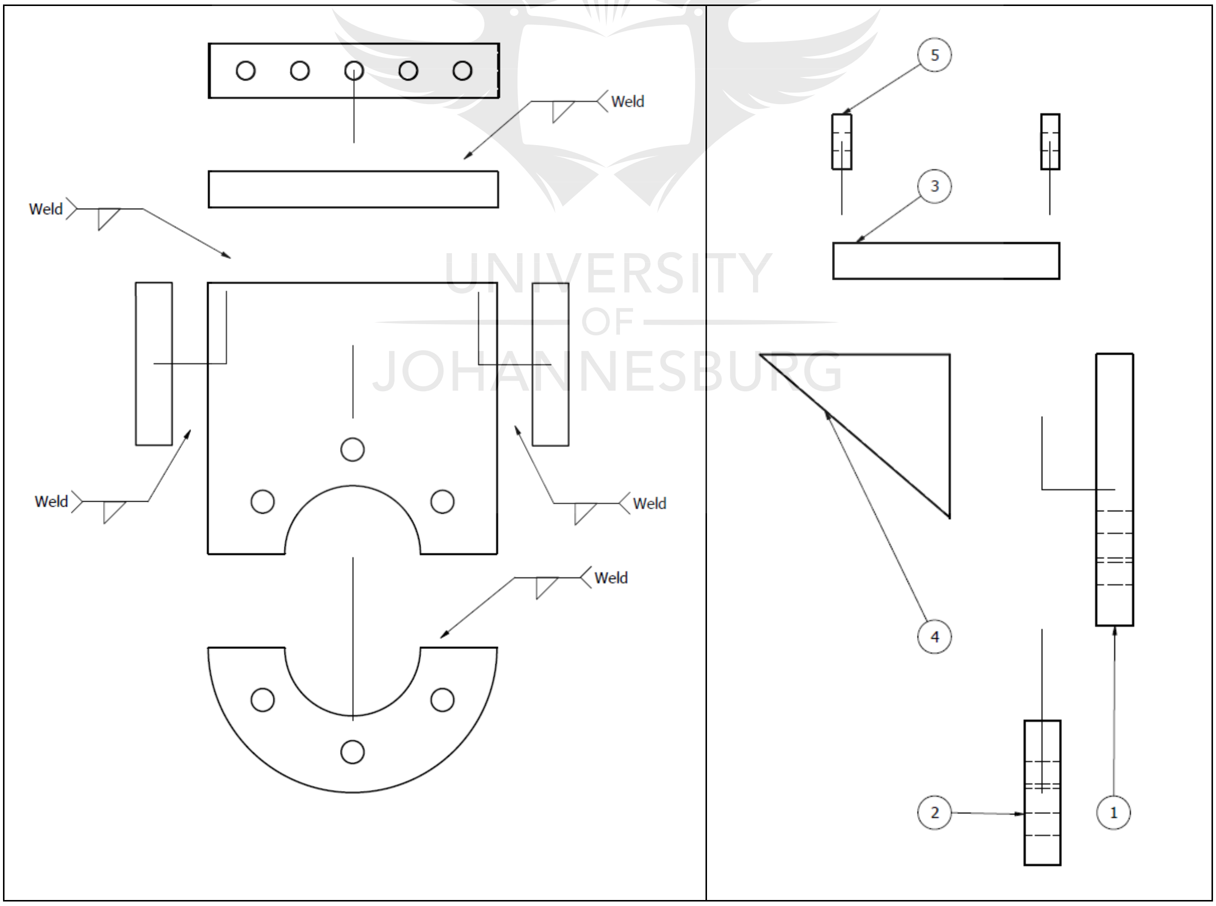


Figure 35 - Hub Bracket Exploded view - Part description

Please as shown in section 4.8.3 for justification of steel plate selection in terms of thickness.

The rear fixed bracket and front swivel bracket both experiences high loads as they connect the H-Sections and Square Tubing of the main structure in front and rear wheels of the system. The components need to be high strength and possess good ductility to give warning before failure.

Table 21 - Hub Bracket Part list

Part List		
Item	**Qty**	**Description**
1	1	Rectangular Piece
2	1	Arc Piece
3	1	Flat Sheet
4	2	Triangular Piece
5	2	Flat Piece

5.5. Split Joint Shaft Manufacturing Process & Material Selection Description.

The split joint shaft is responsible for transmitting the steering cylinder action to the front swivel support bracket to steer the system. The item experiences torsion resistance and the material used is machinable and possess good ductility to give warning before failure. Material for Split Joint Shaft is EN-36A BH 265.

Table 22 - Split Joint Shaft Material Properties & Specifications [28]

Material	Tensile Strength (MPa)	Elongation (%)	Yield Strength (MPa)	Hardness (HB)
4340	920	15	710	270
EN-36A	900	20	730	265

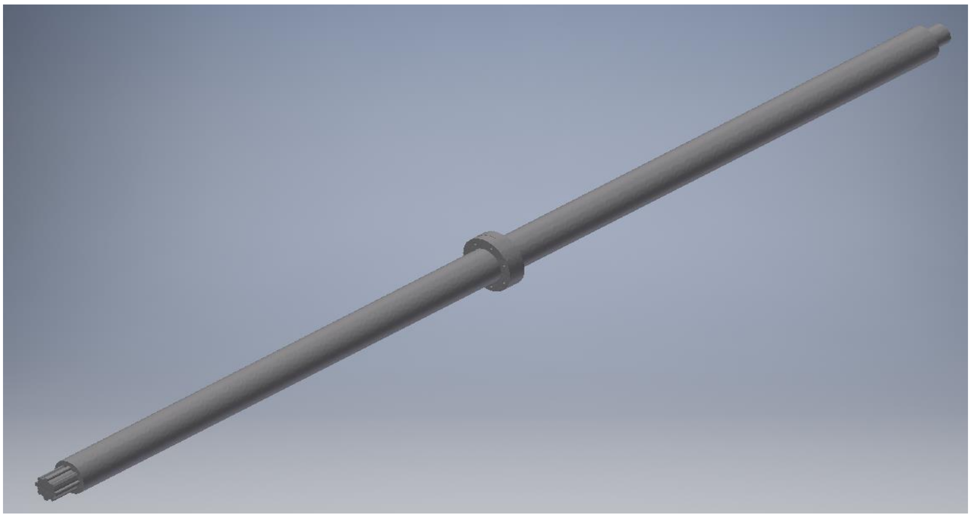


Figure 36 - Split Joint Shaft

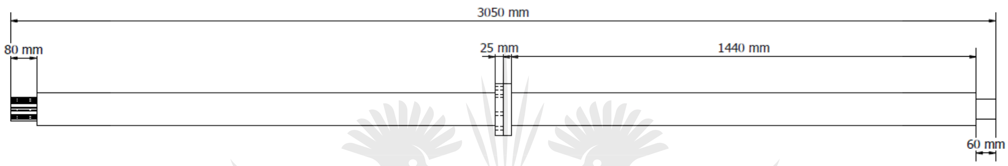


Figure 37 - Split Joint Shaft Technical Drawing

The Split Joint Shaft is 3050 mm long with 100 mm diameter, having a step that is 60 mm long on both ends with 60 mm diameter, as shown in figure 36. The shaft also has a flange coupling feature at mid-center for ease of maintenance and assembly, as shown in figure 38. One side of shaft end has a sprocket feature, as shown in figure 37, where it interconnects with swivel Hub Support Bracket for steering force transmission. The other shaft end is smooth, as shown in figure 39, a steering clamp bracket, as shown in 5.6. with a bore of 60 mm diameter will be mounted onto it and fastened.

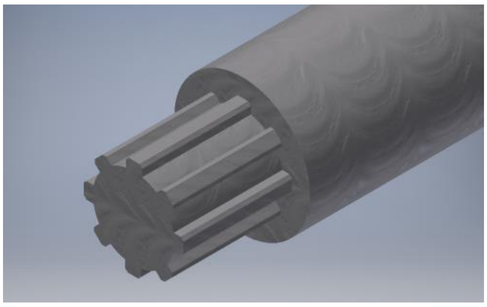


Figure 38 - Shaft End having Sprocket Feature - Illustration

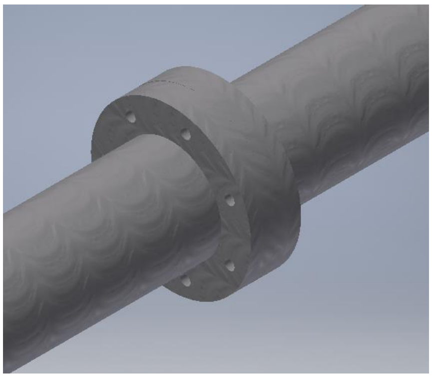


Figure 39 - Shaft Mid Center having Flange Feature - Illustration

Figure 40 - Smooth end Stepped for Steering Cylinder Clamp bracket

5.6. Steering Clamp Bracket Manufacturing Process & Material Selection.

The Steering Clamp Bracket, as shown in figure 40, experiences medium to high stress loads as it transmits torque and steering force (turning force) from the double direction (Left & Right) linear force generated by the Steering Cylinder to the front swivel wheels of the system. The component and material selection are focused on high strength and good ductility material properties for good factor of safety during design verification and operation.

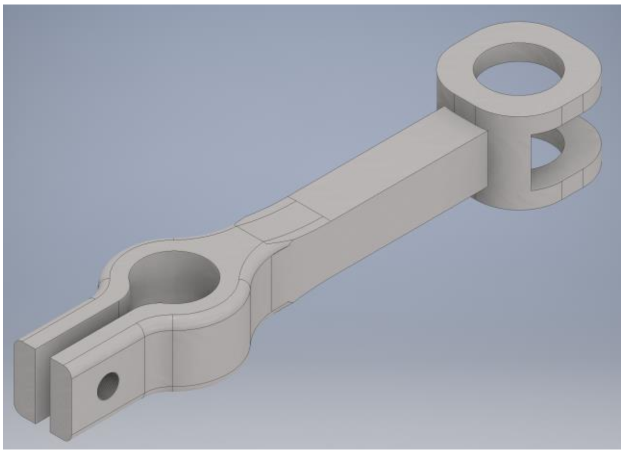


Figure 41 - Steering Clamp Bracket

Table 23 - Steering Clamp Bracket Material Properties [28].

Material	Tensile Strength (MPa)	Elongation (%)	Yield Strength (MPa)	Hardness (Rockwell B)
AISI 1020	420	15%	350	68
Al 6061-T6551 angle unequal leg	276	17.0 %	276	60
EN 10025-2	450	18 %	355	74

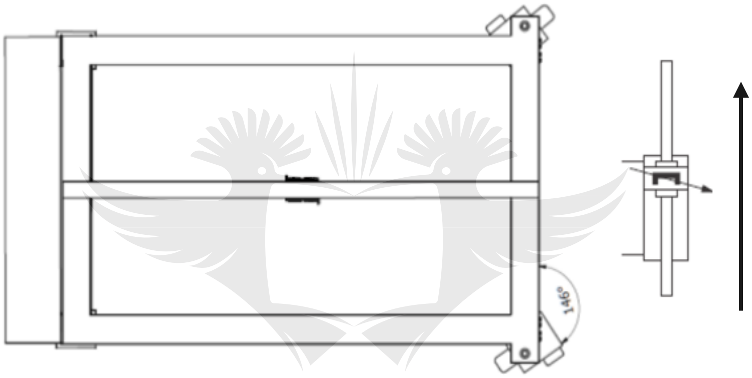


Figure 42 - Steered Wheels Illustration

5.7. Spreader Beam Manufacturing Process & Material Selection.

The H-section & I-section are a standard steel with high strength properties and are considered for the construction of the spreader beam. The spreader beam's structure consists of a combination of four H-section steels, four 60 mm thick hooking plates and four lifting cylinder locating steel plates, all joined using bolt connection method. Material for the spreader beam is SANS 1431, (as shown in table 20).

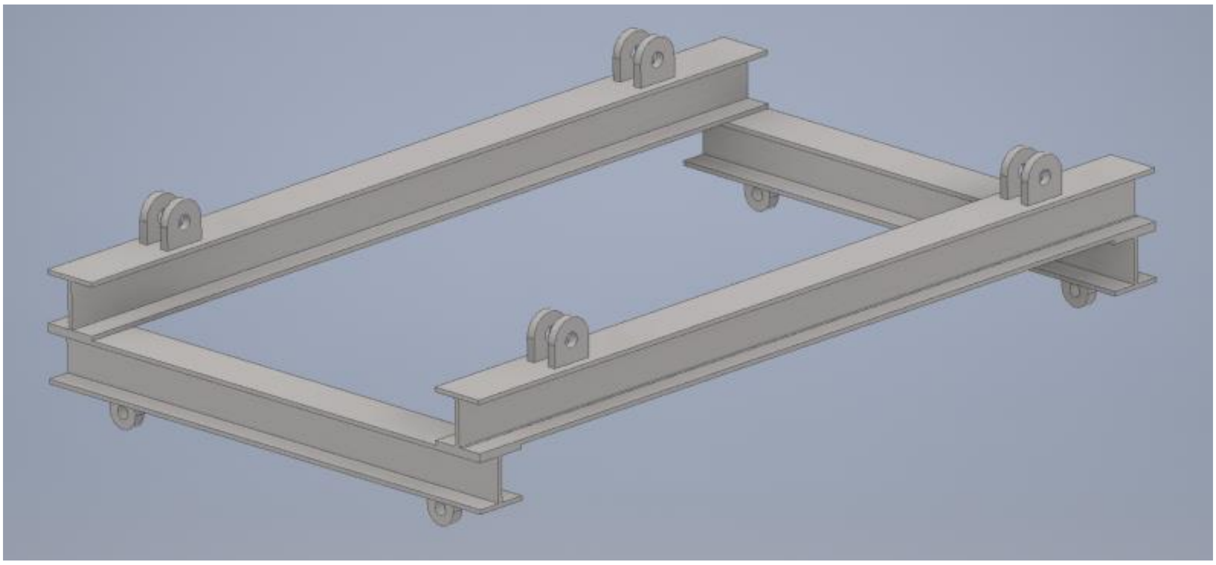


Figure 43 - Lifting Spreader beam

5.8. Chapter Summary

Material selection for the new design system has been chosen according to their reliability and high strength properties. Technical design shapes have been populated as well through Autodesk Inventor Professional. Material chosen of component manufacturing of the new design system are readily available from the market, that means there is no need to mould any component when manufacturing.

CHAPTER SIX

SIMULATION OF NEW DESIGN SYSTEM

6. Chapter Overview

In this chapter, new design system simulation is conducted and clarified. The simulation is done using a technically drawn model from Autodesk Inventor Professional considering different loads applied on the new system design structure. Simulation was conducted to analyse and verify the feasibility of the new design system' main frame structure including its components while in operation under severe conditions and in heavy duty handling. The simulation results summary was used to analyse the performance and validity of material selection of the new system' components through Autodesk Inventor Pro, Stress Analysis simulation feature.

6.1. Model Design Development

The system has been designed using Autodesk Inventor as shown in Figure 22, 44 & 45. In this design, the dimensions and turning radius of the equipment have been studied. The spreader beam is placed 103.9 mm away from back and front frame to prevent the spreader beam from damaging the frame while lifting and lowering. The spreader beam is designed to be 3 m above the ground, making the system to be able to handle loads <3m but with a range of 1 to 2.2 m in height and again load not longer than 3,7 in length. It is important to maintain the specified distance for the spreader beam to have enough space while moving.

6.1.1. New System Design Model Technical Drawings

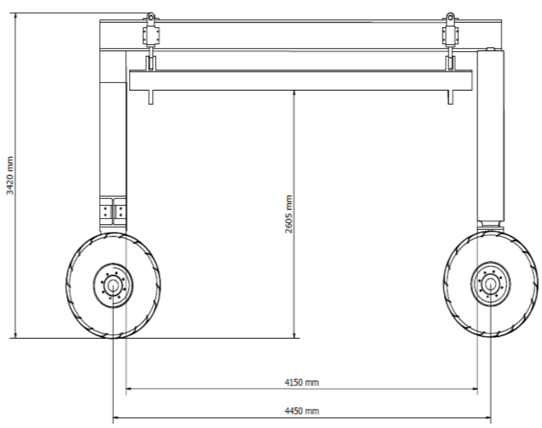


Figure 44 - New System design side view dimensions in (mm)

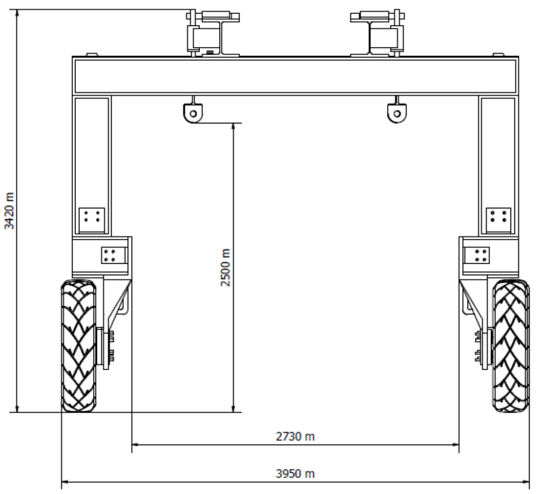


Figure 45 - New System design front view dimensions in (mm)

6.2. New System Design Model Testing

This section provides and overview of the new system design simulation test matrix, as well as defining stress analysis simulation conditions and Engineering Stress Analysis Procedures.

6.2.1. Test Matrix

Test matrix methodology for the new system design is focused on static analysis done to evaluate the behaviour of the proposed model under the action of balancing forces. Static structural analysis evaluates the deformation, strain produced, stress induced and other structural parameters [63]. The procedure in achieving the analysis is done through the steps below:

- Selecting the stress analysis in environment tab on Autodesk Inventor.
- Creating simulation from designed models and assign the material suitable for the column to beam bolted connection.
- Under the loads ribbon selected remote force and located (the face, edges, or vertices) where the force is to be applied precisely.
- Entered load parameters for the magnitude and directions of the force on spreader beam.
- Start simulation repeatedly changing the loads of the system's frame structure.

6.2.2. Stress Analysis Simulation.

- Maximum deflection of a cantilever beam occurs when x=L

- Maximum Von Mises Criterion and principal stresses occurs at x=L
- Maximum Bending stress occurs when x=L

6.2.3. Engineering Stress Analysis Procedure (Steps in FEM)

Stress analysis is an engineering discipline that uses many methods to determine the stresses and strains in materials and structure subjected to forces. It is also a primary task for civil, mechanical, and aerospace engineers involved in the design of structures of all sizes and it is used in the maintenance of such structures and to investigate the causes of structural failures. The method used in this project under the stress analysis is the Finite Element Method, which is for solving problems of engineering and mathematical physics [63]. The use of finite element method includes structural analysis, heat transfer, fluid flow mass transport and electromagnetic potential [36]. The general steps taken in finite element method helps in solving the engineering problem:

- Step 1 Discretize and select the element types,
- Step 2 Select a displacement function,
- Step 3 Define the strain/displacement and stress/strain relationships,
- Step 4 Derive the element stiffness Matrix and Equations,
- Step 5 Assemble the element equations to obtain the global equation and introduce boundary condition,
- Step 6 Solve for the unknown degrees of freedom,
- Step 7 Solve for the element strains and stresses,
- Step 8 Interpret the results.

6.3. FEA Simulation and Results of New System Design in Autodesk Inventor

In this section, simulations for the new system design are carried out. Material Stress Analysis is conducted to determine the strength of each designed component when under 20-ton load and varying loads under 20 – ton. Deflections of materials and safety factors are also determined.

6.3.1. Software Material Physical Properties for Simulation

Table 24 - Software material physical properties for simulation

Name	Steel, Mild	
General	Mass Density	7.85 g/cm^3
	Yield Strength	207 MPa
	Ultimate Tensile Strength	345 MPa
Stress	Young's Modulus	220 GPa
	Poisson's Ratio	0.275 ul
	Shear Modulus	86.2745 GPa

The FEA simulation was conducted to determine the strongest bolted connection between Flange-Flange bolted connection and Flange-Web of the structure of the new system design.

Constraint Name	Reaction Force		Reaction Moment	
	Magnitude	Component (X,Y,Z)	Magnitude	Component (X,Y,Z)
Fixed Constraint:1	49054,1 N	28,3565 N	36534,8 N m	-4781 N m
		-515,956 N		-36219,1 N m
		49051,4 N		333,478 N m

Table 25 - Spreader Beam Reaction Force and Moment on Constraints

Load Type	Remote Force
Magnitude	49050,000 N
Vector X	-22,750 N
Vector Y	-0,011 N
Vector Z	-49049,995 N
Remote Point X	1692,000 mm
Remote Point Y	-1415,000 mm
Remote Point Z	1202,000 mm

Table 26 - Spreader Beam Operating Conditions _ Remote Force:1

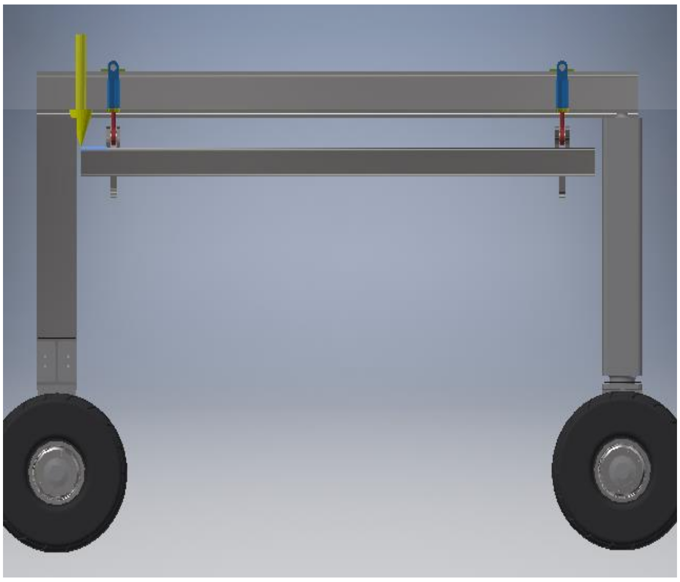


Figure 46 - Selected force(s)

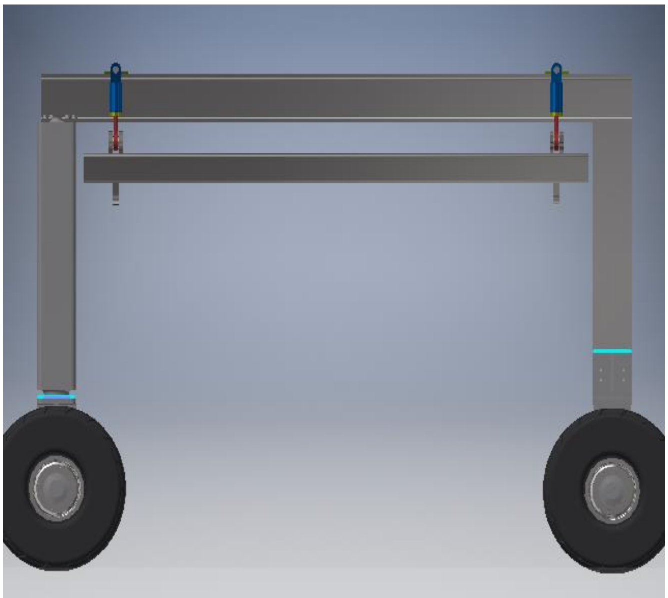


Figure 47 - Fixed Constraints _ Selected Face(s)

6.4. Simulations of New Design Model

Stress analysis of the frame structure is populated so to determine maximum stresses on the structural joints as well as bending moments.

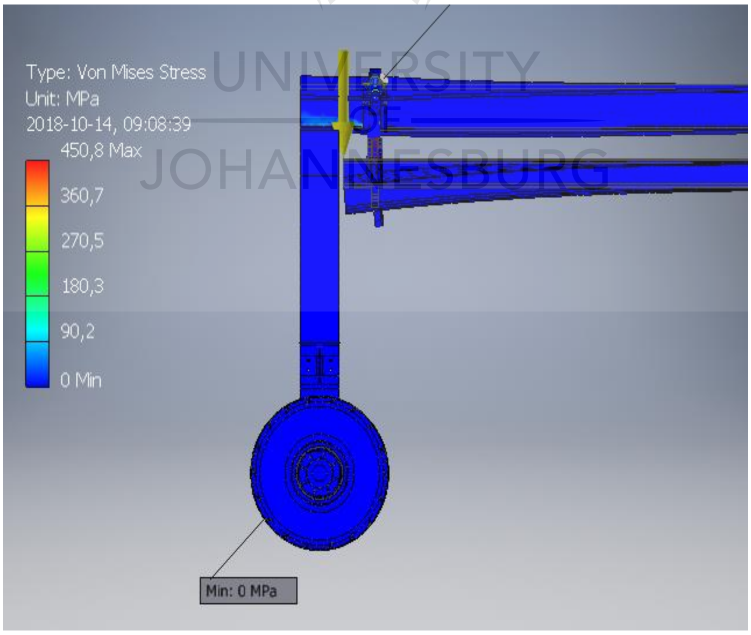


Figure 48 - Von Mises Stress

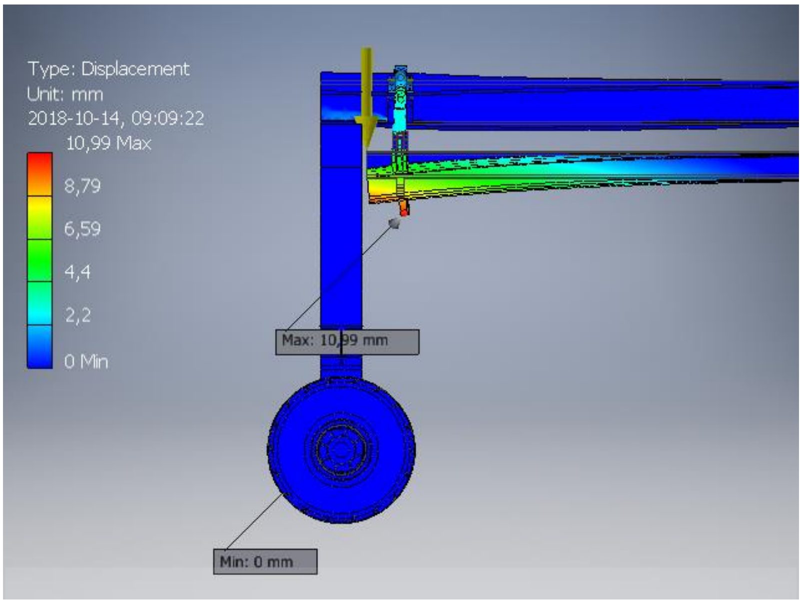


Figure 49 – Displacement

6.5. Discussion of Test Results

Name	Minimum	Maximum
Volume	1122910000 mm^3	
Mass	6426,35 kg	
Von Mises Stress	0 MPa	450,816 MPa
1st Principal Stress	-176,508 MPa	523,069 MPa
3rd Principal Stress	-501,148 MPa	131,308 MPa
Displacement	0 mm	10,9908 mm
Safety Factor	0,459168 ul	15 ul
Stress XX	-368,427 MPa	415,937 MPa
Stress XY	-169,385 MPa	207,724 MPa
Stress XZ	-218,611 MPa	207,78 MPa
Stress YY	-198,681 MPa	185,419 MPa
Stress YZ	-105,036 MPa	127,036 MPa
Stress ZZ	-376,354 MPa	264,963 MPa
X Displacement	-10,2093 mm	3,60794 mm
Y Displacement	-0,400072 mm	1,06964 mm
Z Displacement	-5,89396 mm	1,84734 mm

Figure 50 - Spreader Beam &Structure Result Summary

Upon interpretation of Spreader beam results of Von Mises stress, X Displacement (Vertical direction) and safety factor, it can be verified that the chosen materials and system's overall dimensions meet the requirement for handling a 20-ton load capacity. Von Mises and contact stress values are lesser than the ultimate tensile stress and yield tensile stress of the chosen materials, meaning, the model will operate under 20-ton [63].

6.6. New System Design Bolt Connection Validation and Simulation

No load greater than 25-ton SWL can be used on the developed model. Loads more than 25-ton and less were simulated and safety factors were populated, and they look as illustrated on figure 48, achieving maximum deflection of 17.83 mm which is not safe at all, as shown in 6.9.1.

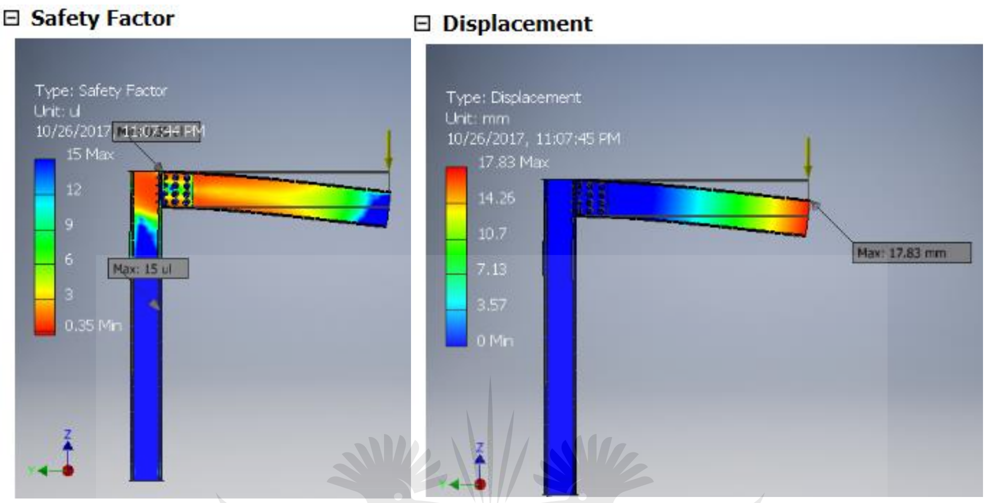
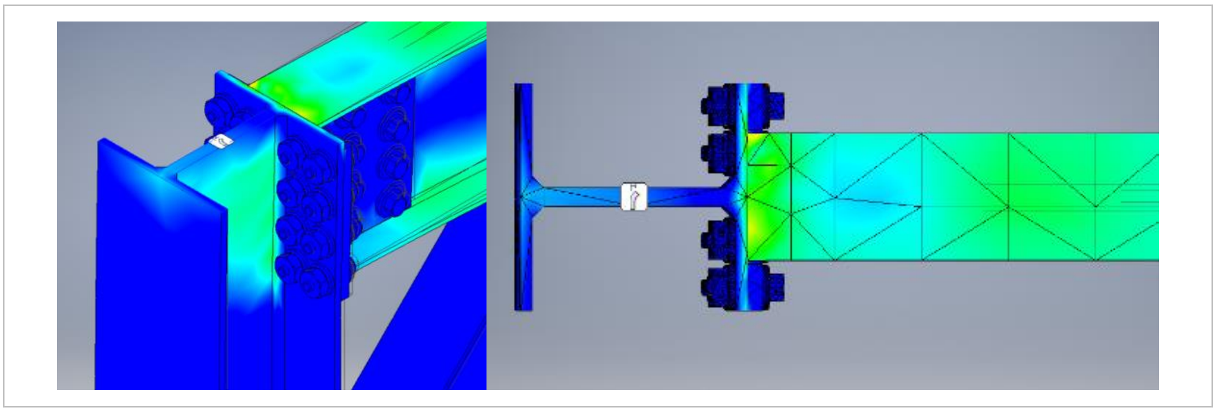


Figure 51 - Safety and Displacement Summary

After FEA simulations of Flange-Flange and Flange-Web bolted connections, it has been noted that a Flange-Flange connection is much stronger and it can resist bending deflection as it achieves minimum values of deflection than a Flange-Web bolted connection, see comparison in visual diagrams below. Therefore, this document recommends the use Flange-Flange bolt connection on beam to beam on main frame structure. Bolt connection simulations were modelled from forces applied on fixed constraints simulation of the entire structure.



(a) (b)

(b) Figure 52 - Flange-Web connection _ Flange experiencing stress concentrations

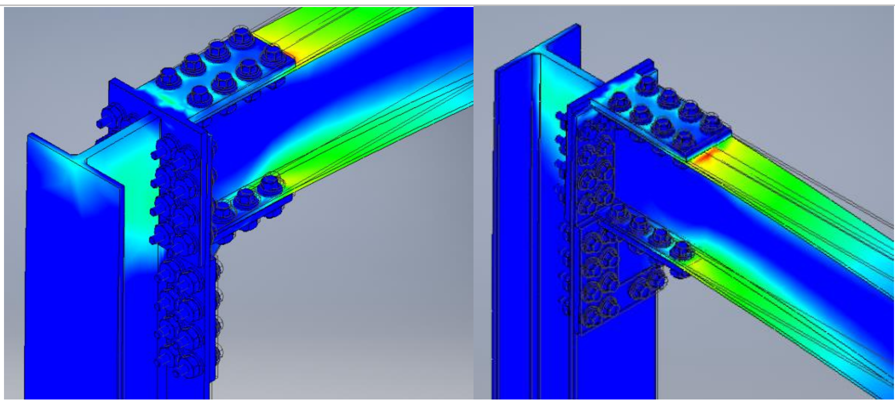


Figure 53 – Flange to Web Stress Distribution points

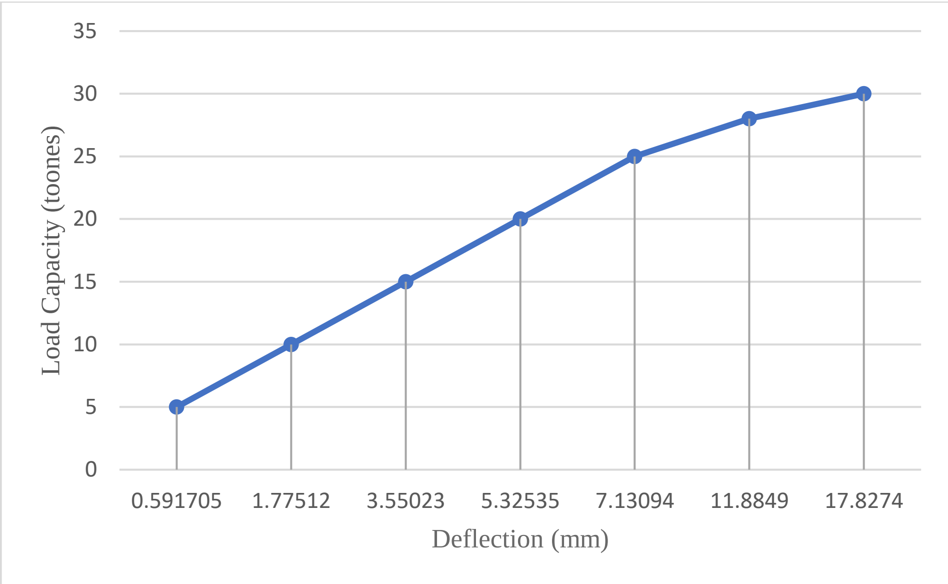
6.7. Summary of Results (Tabular and Graphical)

Flange to Web bolted connection of the main structure graphical analysis and summary of results obtained during FEA simulation in Autodesk Inventor.

Table 27 - New Design System table summary

Load Capacity (**Ton**)	Equivalent Strain	Von Mises Stress	Strain (Z-Z) [ul]	Principal Stress (Z-Z) [MPa]	Deflection (mm)
30	0.00236002	587.904	0.00115692	314.429	17.8274
28	0.00157337	391.942	0.000771281	209.619	11.8849
25	0.000944004	235.16	0.00045871	123.834	7.13094
20	0.000698765	174.125	0.000341154	92.8765	5.32535
15	0.000465846	116.084	0.000227436	61.9171	3.55023
10	0.000232925	58.0426	0.000113718	30.9586	1.77512
5	7.76407E-05	19.3473	0.000037906	10.3196	0.591705

Table 28 - Load vs Deflection Graph



6.7.1. Deflection Limits

Deflection limits are imposed in AS 1418.18 (Standards of Crane and Hoists) on vertical and lateral deflections of beams and columns for the purpose of obtaining satisfactory service performance of lifting devices. The following deflection limits for heavy duty handling serviceability loads, using dynamic factors of 1.0: [37].

Vertical settlement plus axial shortening of a support: $\Delta_z = \pm l/1000$ but not more than 10 mm, (as shown in figure 54) [37]. Therefore, main frame structure' material selection and design are valid as it has been verified through Autodesk Inventor Stress Analysis as 20-ton load simulation gives 5.325 mm deflection, and it falls within <10 mm range, as shown in table 27 & figure 54.

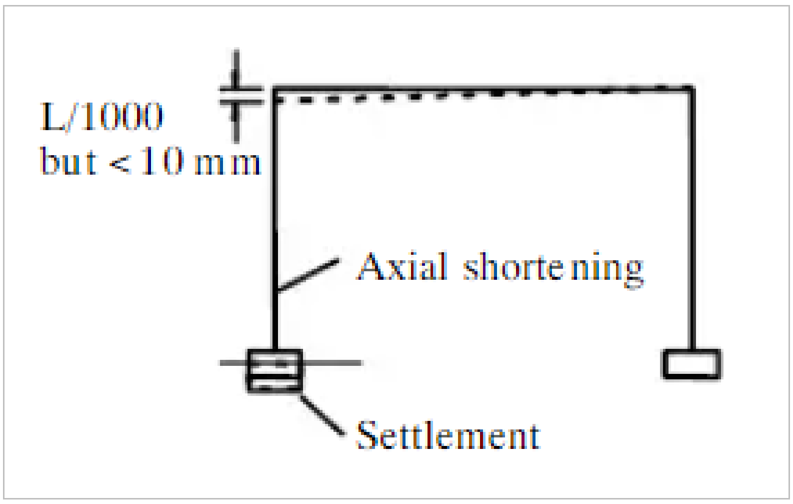


Figure 54 - Column top displacement limit deflection limit [37]

6.8. Spreader Beam Simulation

Spreader beam experiences point load remotely on four hooking points (numbered 2, as shown in figure 55) when the new design system is under load of 20-ton. Each hooking point experiences a quarter of 20-ton weight thus, 49.05 kN. Fixed points (numbered 1, as shown in figure 55), where four hydraulic lifting cylinders are interconnected to the spreader beam.

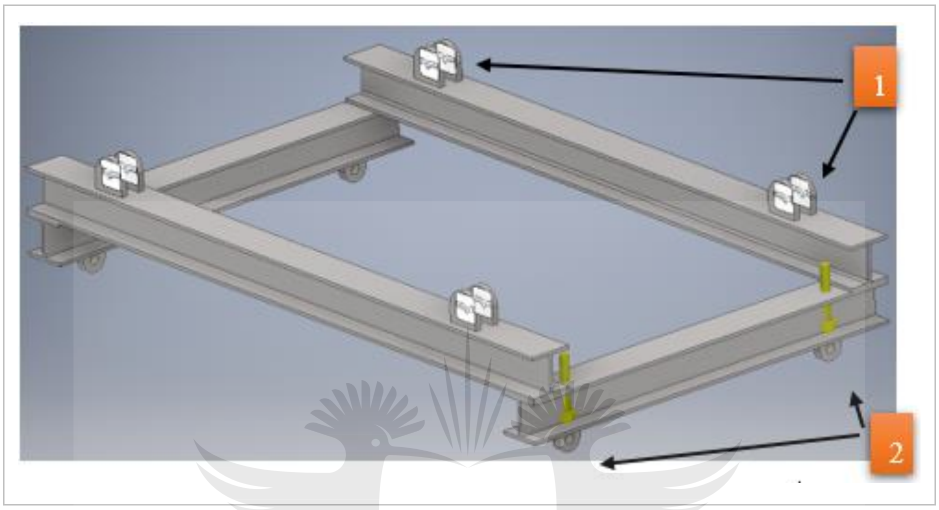


Figure 55 - Spreader Beam Simulation Fixed Constraints & Remote Forces

Table 29 - Spreader Beam Software Material Physical Properties

Name	Steel, Mild, Welded	
General	Mass Density	7,85 g/cm^3
	Yield Strength	207 MPa
	Ultimate Tensile Strength	345 MPa
Stress	Young's Modulus	220 GPa
	Poisson's Ratio	0,275 ul
	Shear Modulus	86,2745 GPa
Part Name(s)	SPREADER BEAM.ipt	

Material	Steel, Mild, Welded
Density	7,85 g/cm^3
Mass	1561,52 kg
Area	19927700 mm^2
Volume	198920000 mm^3
Center of Gravity	x=1247,83 mm y=43,1878 mm z=2000 mm

Table 30 - Spreader Beam Simulation Result Summary

Name	Minimum	Maximum
Volume	198920000 mm^3	
Mass	1561,52 kg	
Von Mises Stress	0,452151 MPa	199,587 MPa
1st Principal Stress	-26,4196 MPa	245,651 MPa
3rd Principal Stress	~~-176,485 MP~~a	43,7975 MPa
Displacement	0 mm	3,82366 mm
Safety Factor	1,03714 ul	15 ul
Stress XX	-133,015 MPa	113,657 MPa
Stress XY	-62,2795 MPa	73,4198 MPa
Stress XZ	-75,8247 MPa	78,4753 MPa
Stress YY	-124,698 MPa	232,538 MPa
Stress YZ	-79,3617 MPa	92,298 MPa
Stress ZZ	-168,194 MPa	195,719 MPa
X Displacement	-3,24796 mm	2,70945 mm
Y Displacement	-3,04309 mm	2,48793 mm
Z Displacement	-1,35787 mm	0,675541 mm
Equivalent Strain	0,00000174764 ul	0,000837591 ul
1st Principal Strain	-0,00000067004 ul	0,000999772 ul
3rd Principal Strain	-0,0007447 ul	-0,000000334485 ul
Strain XX	-0,000621974 ul	0,000517355 ul
Strain XY	-0,000360938 ul	0,000425501 ul
Strain XZ	-0,000439438 ul	0,0004548 ul
Strain YY	-0,000474843 ul	0,00092378 ul
Strain YZ	-0,000459937 ul	0,000534909 ul
Strain ZZ	-0,000696652 ul	0,000830264 ul

6.8.1. Spreader Beam Simulation Discussion

Material chosen for manufacturing of the spreader beam and technical design modelling of the component in terms of shape and dimensions is valid as it has been verified through Autodesk Stress Analysis. According to the component's physical properties, yield strength is 760 MPa (as shown in 5.3) and the maximum Von Mises stress induced by the component is 199.587 MPa giving us a safety factor of 3.81 ul, as shown in table 30 [63, 65]. It has been observed from result summary table, as shown in table 30, that the maximum deflection is 2.709 mm under remote point loads. It can be concluded that the designed spreader beam is reliable and that its operational' life span will last (as shown in table 41, Factor of Safety related to Stress).

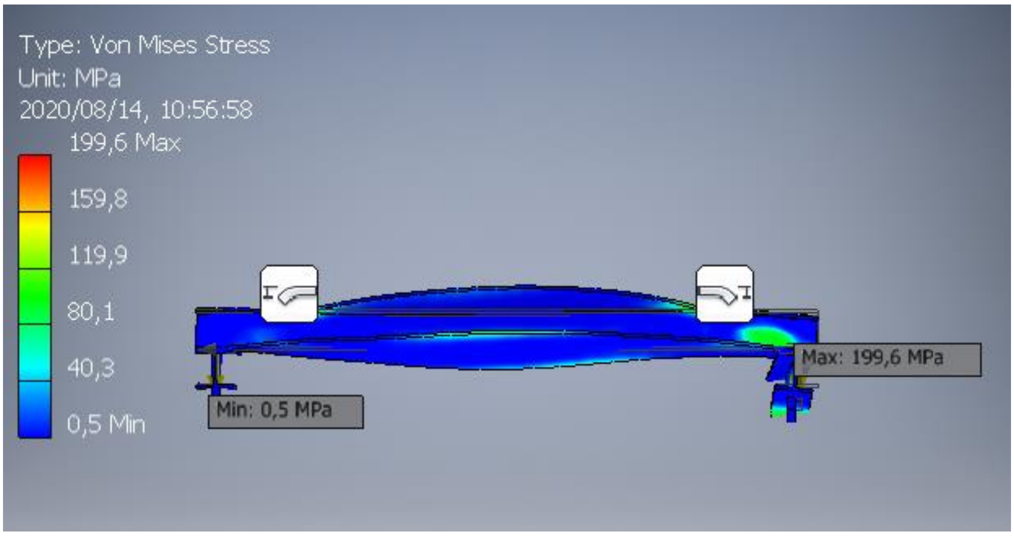


Figure 56 - Spreader Beam Von Mises Stress Distribution Simulation

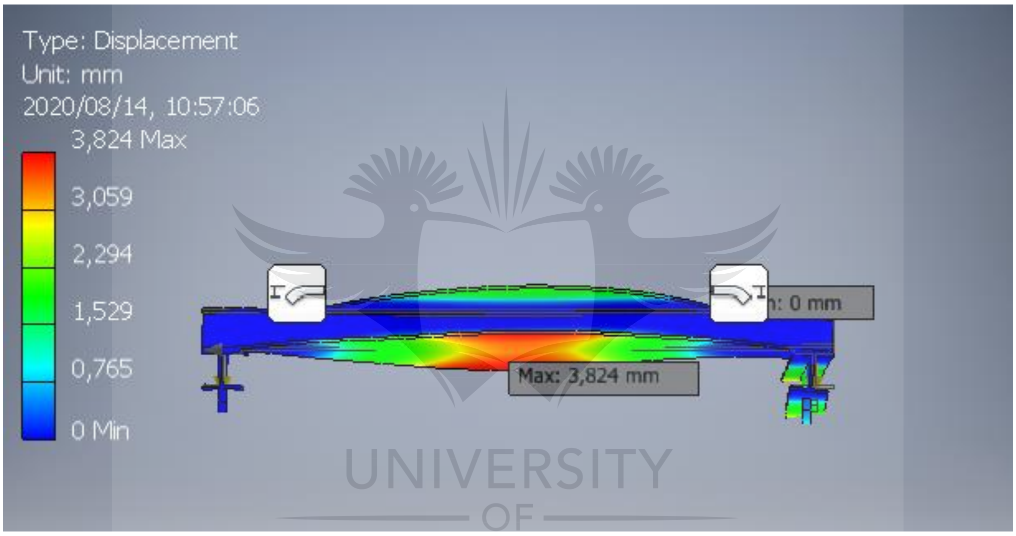


Figure 57 - Spreader Beam Deflection Simulation

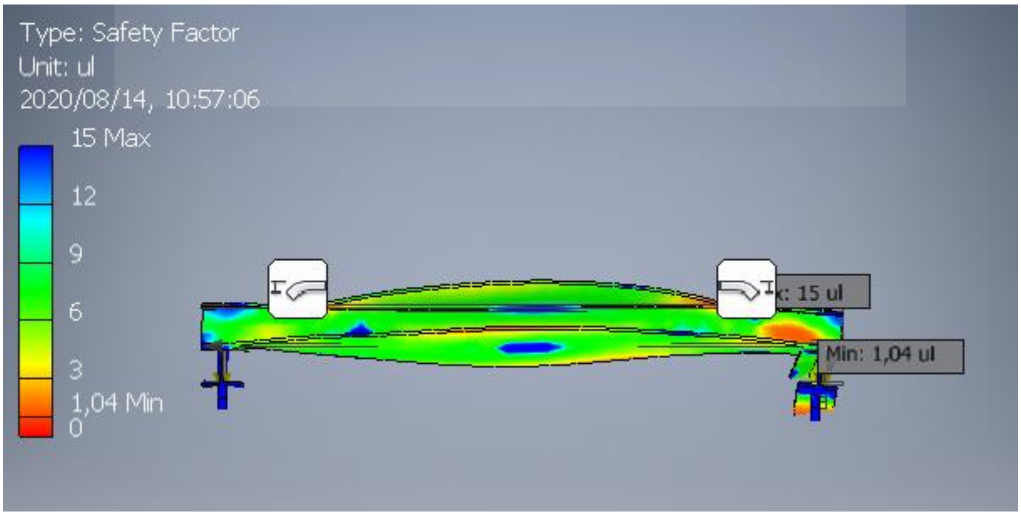


Figure 58 - Safety Factor Stress, Strain & Deflection Distribution Simulation

6.9. Steering Clamp Bracket Simulation

Steering clamp bracket experiences bending stress created by the steering effort applied by the hydraulic steering cylinder when turning the front wheels of the new design system. Steering effort is 278.49 kN and bending moment of 128.1 kN.m values are used for simulation of the clamp bracket, as shown in 4.6 [65].

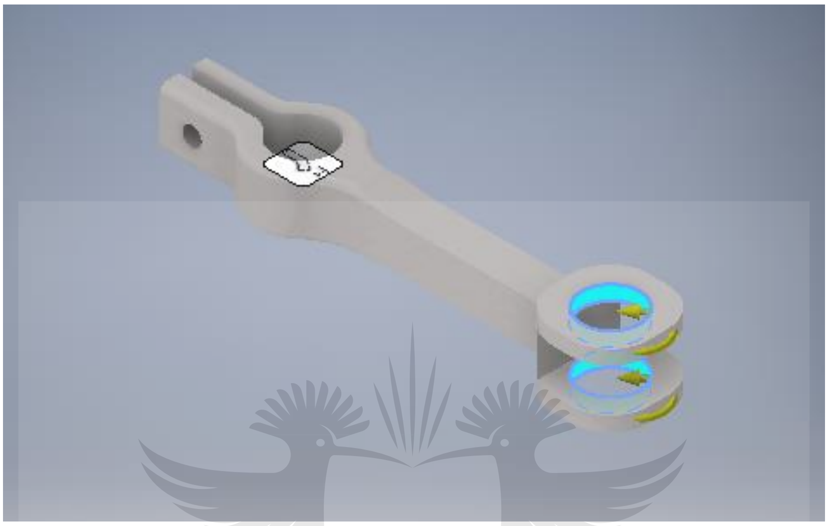


Figure 59 - Steering Clamp Support Bracket Simulation Fixed Constraints & Bending Moment

Table 31 - Steering Clamp Support Software Bracket Material Physical Properties

Material	Steel, Mild, Welded
Density	7,85 g/cm^3
Mass	8,65323 kg
Area	142057 mm^2
Volume	1102320 mm^3
Center of Gravity	x=41,8117 mm y=22,5087 mm z=19,9104 mm

Name	Steel, Mild, Welded	
General	Mass Density	7,85 g/cm^3
	Yield Strength	207 MPa
	Ultimate Tensile Strength	345 MPa
Stress	Young's Modulus	220 GPa
	Poisson's Ratio	0,275 ul
	Shear Modulus	86,2745 GPa
Part Name(s)	Steering Clamp Bracket.ipt	

Table 32 -Steering Clamp Support Bracket Bending Moments

Load Type	Moment
Magnitude	128105,400 N mm
Vector X	0,000 N mm
Vector Y	128105,400 N mm
Vector Z	0,000 N mm

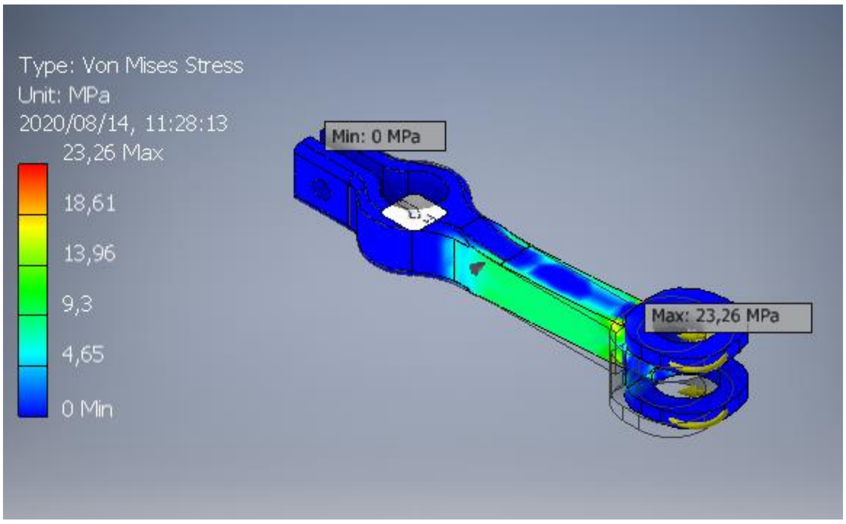


Figure 60 - Von Mises Stress distribution simulation

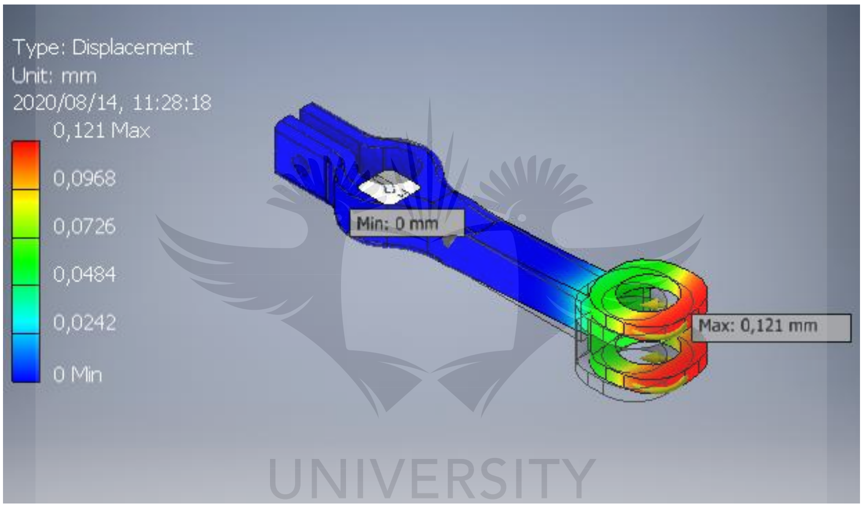


Figure 61 - Bending Moment Deflection simulation

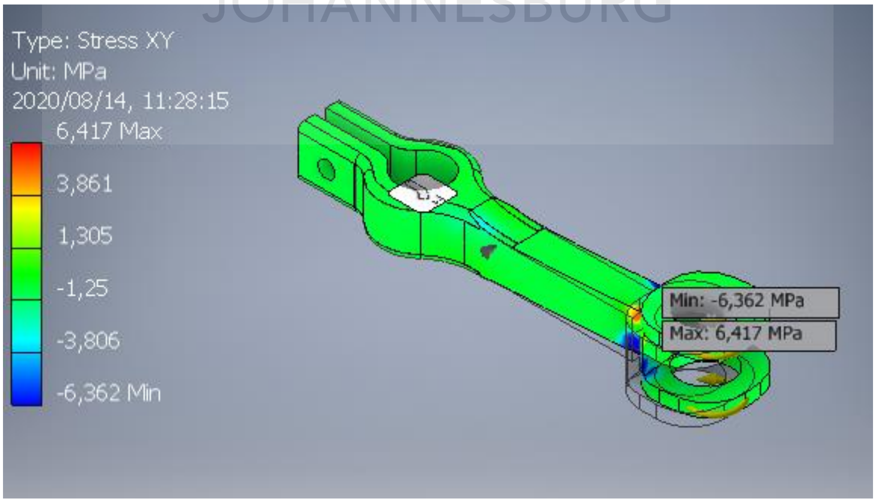


Figure 62 - Strain distribution simulation

Table 33 - Steering Clamp Support Bracket Result Summary

Name	Minimum	Maximum
Volume	1102350 mm^3	
Mass	8,65347 kg	
Von Mises Stress	0,00000573906 MPa	23,2592 MPa
1st Principal Stress	-4,82989 MPa	23,1302 MPa
3rd Principal Stress	-26,8089 MPa	3,72184 MPa
Displacement	0 mm	0,12104 mm
Safety Factor	8,89972 ul	15 ul
Stress XX	-23,6314 MPa	20,8678 MPa
Stress XY	-6,36196 MPa	6,41706 MPa
Stress XZ	-5,74985 MPa	6,27712 MPa
Stress YY	-7,62664 MPa	7,41893 MPa
Stress YZ	-5,0532 MPa	4,73257 MPa
Stress ZZ	-10,3024 MPa	10,2609 MPa
X Displacement	-0,0316743 mm	0,0316501 mm
Y Displacement	-0,0023076 mm	0,00232129 mm
Z Displacement	-0,120888 mm	0,00009877 mm
Equivalent Strain	0,0000000000226994 ul	0,0000955439 ul
1st Principal Strain	0,0000000000238888 ul	0,0000984949 ul
3rd Principal Strain	-0,000112734 ul	0,00000000000159088 ul
Strain XX	-0,0000943188 ul	0,0000853831 ul
Strain XY	-0,0000368704 ul	0,0000371898 ul
Strain XZ	-0,000033323 ul	0,0000363788 ul
Strain YY	-0,0000291724 ul	0,0000274901 ul
Strain YZ	-0,0000292856 ul	0,0000274274 ul
Strain ZZ	-0,0000427802 ul	0,0000428209 ul

6.9.1. Steering Clamp Bracket Simulation Discussion

Material chosen for manufacturing of the steering clamp bracket and technical design modelling of the component in terms of shape and dimensions is valid as it has been verified through Autodesk Stress Analysis. According to the component's physical properties, yield strength is 207 MP and the maximum Von Mises stress induced by the component is 23.26 MPa giving us a safety factor of 8.899ul, as shown in table 31 & 33. It has been observed from result summary table, as shown in table 33, that the maximum deflection is 0.3165 mm under steering effort load. It can be concluded that the designed steering clamp bracket is reliable and that its operational' life span will last almost forever, (as shown in table 41, Factor of Safety related to Stress) [64].

6.10. Rear and Front Swivel Support Bracket Simulation.

Rear and Front Swivel Support Bracket Simulation experiences point loads from the main structure when loaded. The point load exerted on each support brackets is 49.05 kN, (as shown in 4.2.). Correct material as well as the abovementioned force has been used for the simulation.

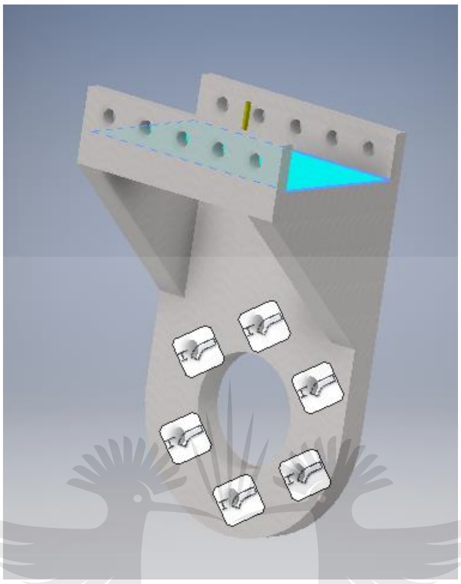


Figure 63 – Rear and Front Swivel Support Bracket Simulation Fixed Constraints _ Selected Face(s) & Force(s)

Table 34 – Rear and Front Swivel Support Bracket Software Material Physical Properties

Name	Steel, Mild, Welded	
General	Mass Density	7,85 g/cm^3
	Yield Strength	207 MPa
	Ultimate Tensile Strength	345 MPa
Stress	Young's Modulus	220 GPa
	Poisson's Ratio	0,275 ul
	Shear Modulus	86,2745 GPa
Part Name(s)	HUB BRACKET.ipt	

Material	Steel, Mild, Welded
Density	7,85 g/cm^3
Mass	78,8227 kg
Area	660213 mm^2
Volume	10041100 mm^3
Center of Gravity	x=0,00088221 mm y=208,568 mm z=74,3887 mm

Table 35 - Simulation Operating Conditions

Load Type	Force
Magnitude	39240,000 N
Vector X	0,000 N
Vector Y	-39240,000 N
Vector Z	0,000 N

Table 36 -Reaction Force, Moments & Constraints

Constraint Name	Reaction Force		Reaction Moment	
	Magnitude	Component (X,Y,Z)	Magnitude	Component (X,Y,Z)
Fixed Constraint:1	39240 N	0 N	3335,87 N m	-3335,87 N m
		39240 N		0 N m
		0 N		0 N m

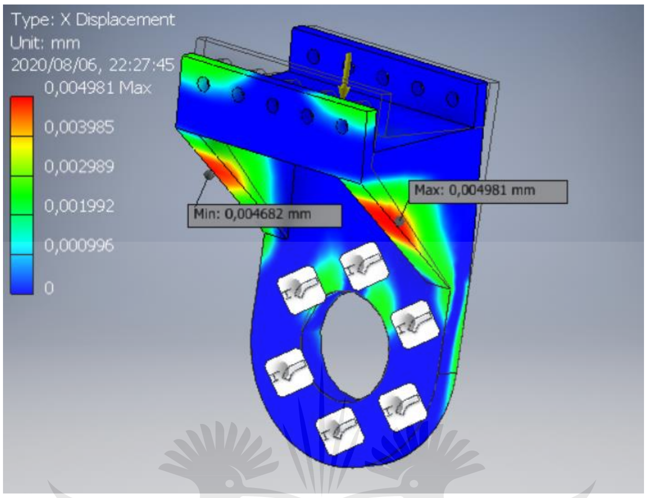


Figure 64 - Rear and Front Swivel Support Bracket X-Displacement Deflection simulation

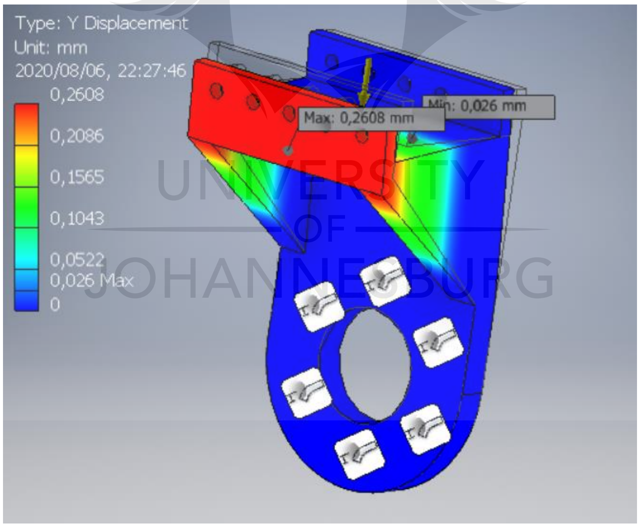


Figure 65 - Rear and Front Swivel Support Bracket Y-Displacement Deflection simulation

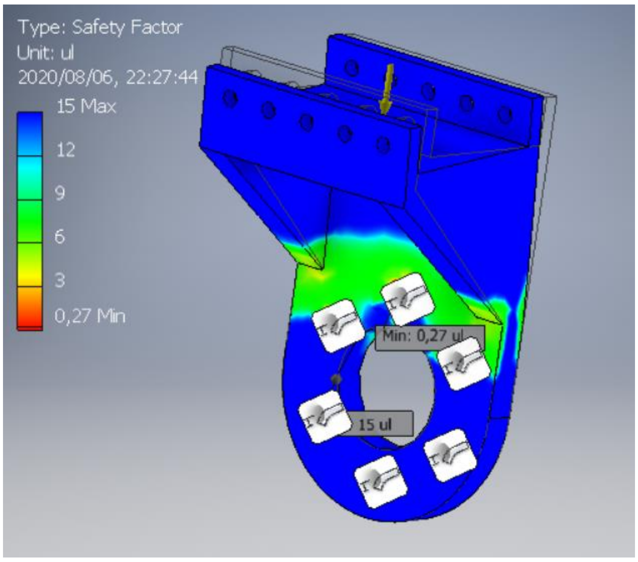


Figure 66 - Rear and Front Swivel Support Bracket Safety Factor Stress Distribution simulation

Table 37 - Rear & Front Swivel Support Bracket Simulation report summary

Name	Minimum	Maximum
Volume	10041100 mm^3	
Mass	78,8227 kg	
Von Mises Stress	0,0569262 MPa	755,754 MPa
1st Principal Stress	-179,256 MPa	215,535 MPa
3rd Principal Stress	-942,627 MPa	58,1363 MPa
Displacement	0 mm	0,403333 mm
Safety Factor	~~0,273899 ul~~	15 ul
Stress XX	-305,673 MPa	136,491 MPa
Stress XY	-100,644 MPa	94,6935 MPa
Stress XZ	-116,726 MPa	165,258 MPa
Stress YY	-526,885 MPa	106,127 MPa
Stress YZ	-30,1799 MPa	414,096 MPa
Stress ZZ	-593,236 MPa	136,979 MPa
X Displacement	-0,00468223 mm	0,00498121 mm
Y Displacement	-0,260761 mm	0,025957 mm
Z Displacement	-0,00994305 mm	0,313005 mm
Equivalent Strain	0,000000220781 ul	0,00316961 ul
1st Principal Strain	0,0000000901073 ul	0,00111162 ul
3rd Principal Strain	-0,0037194 ul	-0,000000135153 ul
Strain XX	-0,000559427 ul	0,000358539 ul
Strain XY	-0,000583278 ul	0,000548792 ul
Strain XZ	-0,00067648 ul	0,000957746 ul
Strain YY	-0,00127129 ul	0,000408708 ul
Strain YZ	-0,000174906 ul	0,00239987 ul
Strain ZZ	-0,00165583 ul	0,000380224 ul

6.10.1. Rear and Front Swivel Support Bracket Simulation Discussion

Material chosen for manufacturing of front swivel & rear support bracket and technical design modelling of the component in terms of shape and dimensions is valid as it has been verified through Autodesk Stress Analysis. According to the component's physical properties, yield strength is 760 MP and the maximum Von Mises stress induced by the component is 755.754 MPa giving us a safety factor of 1.5, (as shown in table 37). Support brackets is formed by means of fabrication of 40 mm steel plates to form a strong reinforced supportive structure hence it has been observed from result summary table, (as shown in table 37), that the maximum deflection is 0.004981 mm under remote point load. It can be concluded that the designed Rear and Front Swivel Support Bracket is reliable and that its operational' life span will last, (as shown in table 41, Factor of Safety related to Stress) [65].

6.11. Split Joint Steering Shaft

Split joint steering shaft experiences bending stress at the top end section. The bending stress is transmitted through the steering clamp bracket from the steering cylinder, as shown in 7.3.2. that is creating a steering effort of 278.49 kN, as shown in 4.6. Correct material for the shaft and bending moment of 128.1 kN.m is used for simulation of the shaft.

Figure 67 - Split Joint Steering Shaft Simulation Fixed Constraints & Forces

Table 38 - Split Joint Steering Shaft Material Physical Properties

Name	Steel, Mild, Welded	
General	Mass Density	7,85 g/cm^3
	Yield Strength	207 MPa
	Ultimate Tensile Strength	345 MPa
Stress	Young's Modulus	220 GPa
	Poisson's Ratio	0,275 ul
	Shear Modulus	86,2745 GPa
Part Name(s)	Split joint shaft 1.ipt Split joint shaft.ipt	

Mass	187,613 kg
Area	1042640 mm^2
Volume	23899700 mm^3
Center of Gravity	x=913,052 mm y=8,92936 mm z=0 mm

Table 39 - Split Joint Steering Shaft Simulation Moments

Load Type	Moment
Magnitude	128100,000 N mm
Vector X	-128100,000 N mm
Vector Y	0,000 N mm
Vector Z	0,000 N mm

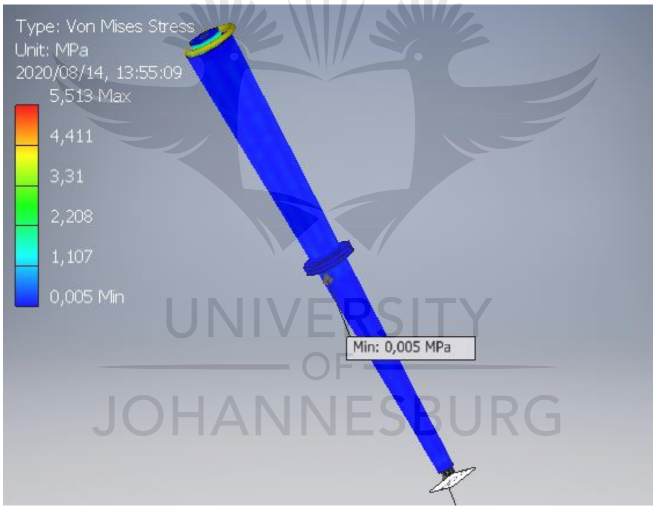


Figure 68 - Split Joint Steering Shaft Von Mises Stress Distribution Simulation

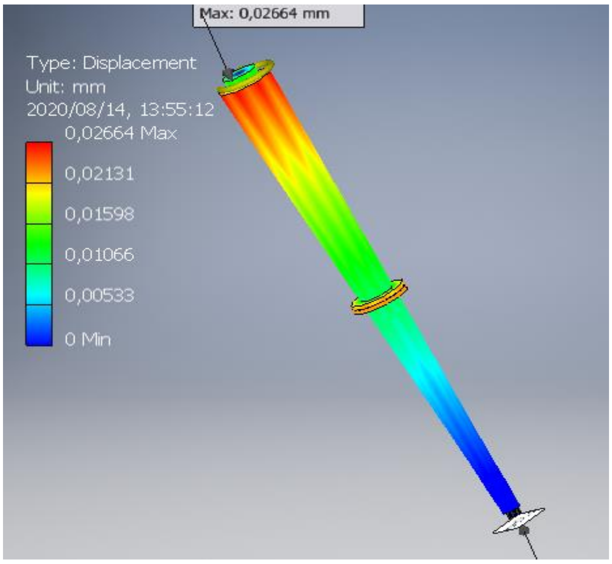


Figure 69 - Split Joint Steering Shaft Deflection Simulation

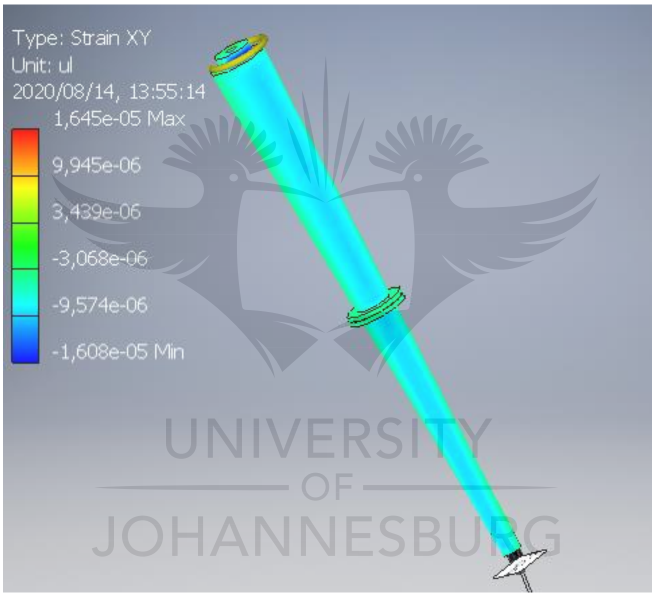


Figure 70 - Split Joint Steering Shaft Strain Distribution Simulation

Table 40 - Split Joint Shat Simulation Summary

Name	Minimum	Maximum
Volume	23899700 mm^3	
Mass	187,613 kg	
Von Mises Stress	0,00494017 MPa	5,51293 MPa
1st Principal Stress	-0,478937 MPa	3,75071 MPa
3rd Principal Stress	-4,05409 MPa	0,225034 MPa
Displacement	0 mm	0,026639 mm
Safety Factor	15 ul	15 ul
Stress XX	-3,20165 MPa	3,02239 MPa
Stress XY	-2,77458 MPa	2,8386 MPa
Stress XZ	-2,85802 MPa	2,83671 MPa
Stress YY	-1,85513 MPa	2,00857 MPa
Stress YZ	-0,917423 MPa	0,924027 MPa
Stress ZZ	-2,24088 MPa	2,01958 MPa
X Displacement	-0,000146581 mm	0,000140993 mm
Y Displacement	-0,026639 mm	0,0264662 mm
Z Displacement	-0,0265661 mm	0,0265998 mm
Equivalent Strain	0,0000000262793 ul	0,0000213011 ul
1st Principal Strain	0,00000000411018 ul	0,0000179219 ul
3rd Principal Strain	-0,0000189497 ul	-0,0000000185943 ul
Strain XX	-0,0000124059 ul	0,0000120466 ul
Strain XY	-0,00001608 ul	0,000016451 ul
Strain XZ	-0,0000165635 ul	0,00001644 ul
Strain YY	-0,000007571 ul	0,0000079045 ul
Strain YZ	-0,00000531688 ul	0,00000535515 ul
Strain ZZ	-0,0000922981 ul	0,0000076111 ul
Contact Pressure	0 MPa	0,241647 MPa
Contact Pressure X	-0,103542 MPa	0,143942 MPa
Contact Pressure Y	-0,192982 MPa	0,202494 MPa
Contact Pressure Z	-0,21318 MPa	0,201775 MPa

6.11.1. Split Joint Shaft Simulation Discussion

Material chosen for manufacturing of the split joint shaft and technical design modelling of the component in terms of shape and dimensions is valid as it has been verified through Autodesk Inventor’s Stress Analysis. According to the component’s physical properties, yield strength is 207 MP and the maximum Von Mises stress induced by the component is 5.513 MPa giving us a safety factor of 15 ul, (as shown in table 38 & 40). It has been observed from result summary table, (as shown in table 39), that the maximum deflection is 0.000141 mm under steering effort load. It can be concluded that the designed steering clamp bracket is reliable and that its operational’ life span will last, (as shown in table 41, Factor of Safety related to Stress) [65].

6.12. Factor of Safety

Factor of safety expresses how much stronger a system is than it needs to be for an intended load. Safety factors are often calculated using detailed analysis because comprehensive testing is impractical on many projects, such as bridges and buildings, but the structure's ability to carry a load must be determined to a reasonable accuracy [38].

Table 41 - Factor of Safety related to Stress [29].

Applications	Factor of Safety - *FOS* -
For use with highly reliable materials where loading and environmental conditions are not severe and where weight is an important consideration	1.3 - 1.5
For use with reliable materials where loading and environmental conditions are not severe	1.5 - 2
For use with ordinary materials where loading and environmental conditions are not severe	2 - 2.5
For use with less tried and for brittle materials where loading and environmental conditions are not severe	2.5 - 3
For use with materials where properties are not reliable and where loading and environmental conditions are not severe, or where reliable materials are used under difficult and environmental conditions	3 - 4

Factor of safety equation,

$$Factor\ of\ \ Safety = \frac{yield\ stress}{working\ stress} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

CHAPTER SEVEN

HYDRAULICS SYSTEM ANALYSIS OF THE NEW DESIGN SYSTEM

7. Chapter Overview

The aim of this chapter is to provide an overview of component selection, background, and analysis of the hydraulic system of the new design. Detailed description and functionality of the hydraulic system components have been provided. Again, new design system' hydraulic circuit systems for steering cylinder, lifting cylinder and hydraulic wheel hubs have been designed an explained.

7.2. Hydraulic Systems Background

Hydraulics involves the use of hydraulic fluids to perform mechanical work. Mechanical work is necessary in order to carry out movements and generate forces. The function of hydraulic drives is to convert the energy stored in hydraulic fluid into motion [39].

7.2.1. Hydraulics Applications Category in Automation Technology/Industry

Two Hydraulics Application Categories are namely.

Stationary hydraulics:

- Production and assembly machines
- Transfer lines
- Lifting and conveying devices
- Presses

Mobile Hydraulics:

- Construction machinery
- Tippers, excavators, elevating platforms
- Lifting and conveying devices (Material Hnandling systems)
- Agricultural machinery

7.2.2. Selection Criteria for New Design System Power Source Components

New design system’s working media are Electric current (electrics) & Fluids (hydraulics) and the operation of the new design system will require a combination of the abovementioned media.

7.3. Description of Main Hydraulic System Components the New System Design

This section provides descriptions of selected hydraulic components suitable for the new system’s operational design requirements.

7.3.1. Hydraulic Wheel Hub/Motor of the New System Design

Hydraulic motors and semi rotary actuators drives (rotary drives) to generate rotary movements. The function of hydraulic drives is to convert the energy stored in hydraulic fluid into motion. In this paper Hydraulic Wheel Hubs are used to drive the overall structure of the new design system, as shown in figure 71 for illustration.

Figure 71 - Hydraulic Wheel Hub/Motor [40].

7.3.2. Hydraulic Linear Cylinders of the New System Design

Cylinders (linear drives) for the generation of straight linear movements, thus enhancing the new design system to be able to lift and lower 30-ton load capacity. Cylinders (linear drives) also will serve as steering system for the new design. The system will use Four double acting cylinders for lifting the load through the support of spreader beam and another two double acting cyliners will be used for extention of the structure as the structure is adjustable. One double rod end hydraulic cylinder will be used for steering mechanism for the system. As shown in figure 72 for illustration [39].

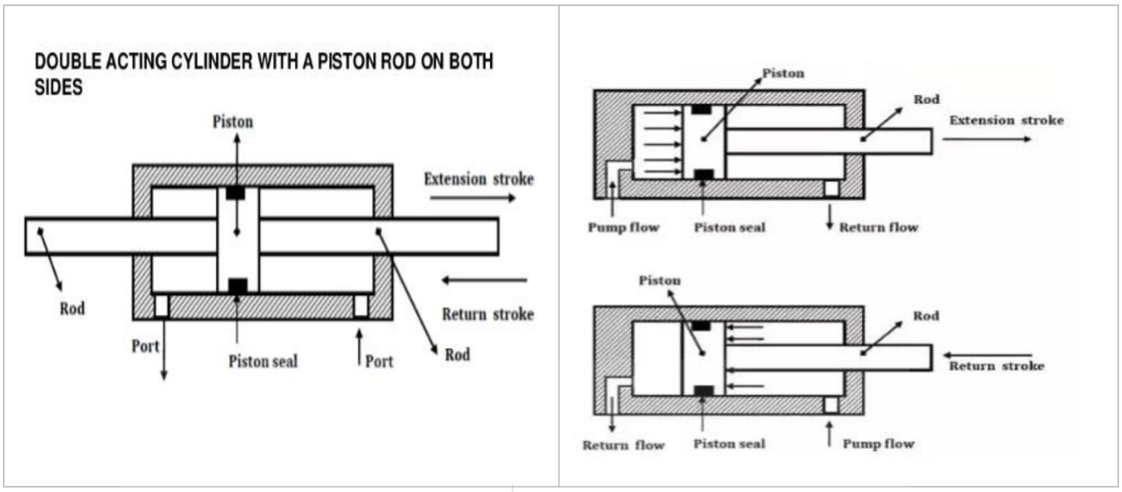


Figure 72 - Steering cylinder diagram & Double acting Lifting cylinder [40, 41]

7.3.3. Hydraulic Power Pack of New System Design

Hydraulic power pack is the hydraulic flow supplier to the system which is considered the power transmitter, as shown in figure 73 for illustration [39].

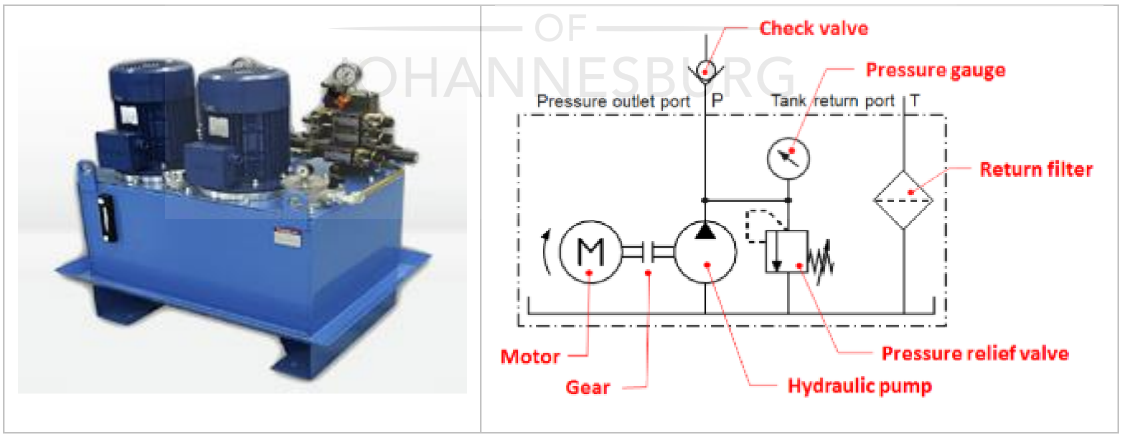


Figure 73 - Hydraulic power pack diagram and circuit [41, 42].

Hydraulic Power Pack Components

- Drive Motor with Electrical Motor (Electrical Energy _ AC/DC)
- Pump
- Reservoir

- Filter
- Pressure Relief Valve

7.3.4. Accumulator for New System Design

The accumulator will be used in order to keep an even pressure in the system when the various valves open and close, as shown in figure 74 for illustration. When hydraulic flow encounter resistance in a system, pressure is built up, Pressure Relief Valve will then be Opened, Flow will Divided by Relief Valve, Flow to Circuit will be Reduced [39].

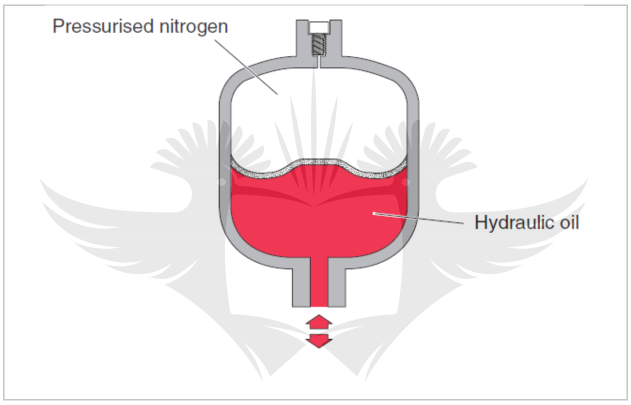


Figure 74 - Accumulator Diagram [39].

7.4. Tire/Wheel selection for the New System Design

New design system is expected to be operated in outdoor & rough terrain, cold environments, oil spilled areas, sensitive, and warehouse applications. Outdoor and rough-terrain applications generally use pneumatic or solid pneumatic tires since they offer better traction and increased stability on uneven, loose terrain. Therefore, the new sytem will be using Solid Pneumatic tires for over design purposes, (as shown in table 42) [43].

7.4.1. Air Pressure

One should check the air pressure on your pneumatic tires before each use. If that isn't possible, try to check daily. Recommended tire pressure can be found on the sidewall of the tire. Why does air pressure matter? Under-inflated tires lead to poor traction, which can cause accidents.

Over-inflated tires can cause a blowout, which causes downtime and profit loss. Checking tire air pressure is an easy way to avoid more serious problems that reduce productivity [43].

Table 42 - Material Handling Tire Comparison Chart [43].

	PRESS-ON (CUSHION)	POLYURETHANE	SOLID PNEUMATIC	PNEUMATIC
Indoor	Yes	Yes	Yes	Yes
Outdoor *(Light)*	Yes	No	Yes	Yes
Outdoor *(Rough Terrain)*	No	No	Yes	Yes
Debris In Work Area	No	No	Yes	No
Lifespan	Medium	Long	Long	Medium
Durability	High	High	High	Medium

Comparison charts are based on general data. Lifespan, durability and cost will depend on the operator, application and usage.

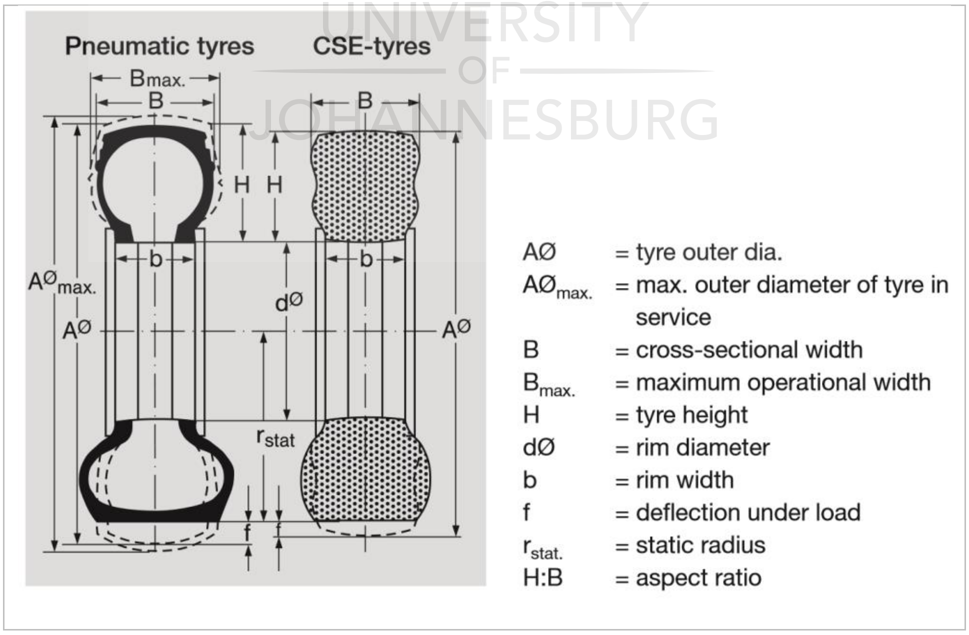


Figure 75 - Tire Configuration [43].

Table 43 - Tire Capacity Specifications [43].

Size	Rim	Overall Diameter	Section Width	Other Vehicles	Forklift 25km/h	
				Static	Load Wheel	Steering Wheel
8.25-20	6.5-20	954	230	5,510	4,380	3,650
280/50-15	8.0-15	670	255	6,040	5,200	4,000
355/45-15	9.75-15	692	287	6,610	5,690	4,375
355/50-15	9.75-15	710	284	6,610	5,690	4,375
300-15	8.0-15	812	255	6,795	5,850	4,500
9.00-20	6.5-20	974	220	6,795	5,400	4,500
10.00-20	8.0-20	1,009	250	7,550	6,000	5,000
11.00-20	8.0-20	1,040	260	8,230	6,540	5,450
355/65-15	9.75-15	812	284	9,060	7,800	6,000
12.00-20	10.0-20	1,090	313	9,815	7,800	6,500
355/50-20	10.0-20	834	310	10,420	8,970	6,900
400/60-15	11.00-15	815	325	10,420	8,970	6,900
12.00-24	10.0-24	1,181	295	11,325	9,000	7,500
465/55-20	16.0-20	1,029	465	13,590	10,800	9,000
14.00-24	10.0-24	1,325	331	13,970	11,100	9,250
16.00-25	11.25-25	1,445	410	18,875	15,000	12,500

Note: The system will be operating under 20-ton load capacity, therefore tire capacity for each wheel of the system is chosen to be 5510 kg load exerted in each of the four wheels of the system @ static position, size 8.25-20 mm and rim size 6.5-20 mm, (as shown in table 43).

Table 44 - Industrial Tire/Rim size selection [43].

Lock Ring Wheels

PREMIUM INDUSTRIAL WHEELS 20" - 24"

Diameter	Wheel Size	Tire Size
20”	6.5-20	8.25-20
	6.5-20	9.00-20
	7.0-20	10.00-20
	7.0-20	9.00-20
	7.5-20	10.00-20
	7.5-20	31x10-20
	7.5-20	31x12-20
	7.5-20	36x14-20
	8.0-20	10.00-20
	8.0-20	11.00-20
	8.0-20	12.00-20
	8.5-20	12.00-20
	10.0-20	12.00-20
	10.0-20	355/50-20
	10.0-20	40x14-20
	16.0-20	465/55-20
24”	8.5-24	12.00-24
	10.0-24	12.00-24
	10.0-24	14.00-24

Wheel configuration

4 Pieces
Heavy Duty application

3 Pieces
Standard application

2 Pieces
Light application

Note: 4 Pieces type Rim (20 inch = 508 mm rim diameter) is used for the new design system as it meets the requirements of heavy duty handilng application. Where the tire overall diameter is 954 mm [63].

7.5. Hydraulic Circuit Modelling of the New System Design components

The aim of this section is to provide detailed descriptions for hydraulic circuit designs of hydraulic steering and lifting cylinders closed loop systems as well as hydraulic wheel hub motors.

7.5.1. Lifting and Lowering of Load Circuit Design and Operation Illustration.

The new design system consists of four double acting hydraulic lifting cylinders attached to the top section of the main frame. These four hydraulic cylinder interconnect the spreader beam to the main frame structure. Therefore, each hydraulic (linear) cylinder in four lifting cyliners will exert ¼ of 20-ton load capacity. Only one double acting hydraulic cylinder will be analysed since all cylinders will be experiencing same force simultaneously when lifting and lowering loads [64]. Again, the new design system consists of two double acting cylinders to perform extraction and retraction enabling the system to be adjuatable. Therefore its retraction and ectraction process is the same as for the lifting cylinders and they are explained below.

A) Hydraulic Lifting Cylinders Circuit System Design & Functionality Description

The diagram consists of hydraulic power pack, 4/2 Way mono-stable Valve and double acting cylinder. Below, is the description of extraction and retractrion process of the lifting cylinders.

In normal position hydraulic circuit operation illustration:

- ✓ Port ***A*** Port ***T***
- ✓ Port ***P*** Port ***B***
- ✓ Cylinder in Retracted End Position.

When actuated (Lowering process), hydraulic circuit operation illustration:

- ✓ Port ***A*** Port ***P***
- ✓ Port ***B*** Port ***T***
- ✓ Cylinder moves to Extracted End Position.

When De-actuated (Lifting process), hydraulic circuit operation illustration:

- ✓ Back to normal position.
- ✓ Port ***A*** Port ***T*** _ Depressurized
- ✓ Port ***B*** Port ***P*** _ Pressurized

Cylinder moves back to Retracted end Position.

As shown in figure 76,

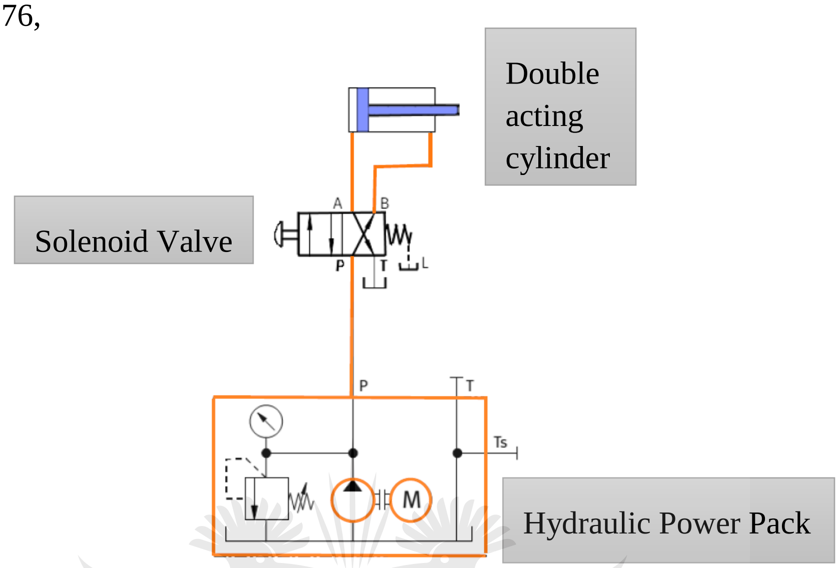


Figure 76 - Lifting cylinders circuit [39].

7.5.2. Hydraulic Wheel Hub Motor Circuit Design & Functionality illustration.

Forward and reverse driving of adjustable hydraulic motors with two directions of rotation. The system consists of four hydraulics motors or wheel hubs. Therefore, each hydraulic (two directions of rotation) motor in four hydraulic motors of the new design system will experience traction effort per ¼ of 30-ton load capacity including the structure's weight. Only one hydraulic motor will be analysed since all drive motors will be experiencing same traction force simultaneously when loads from one place to another [63, 64].

A) Hydraulic Wheel Hub Motor Circuit System Design & Functionality Description

The diagram consists of hydraulic power pack, 4/2 Way mono-stable Valve, flow control valve and hydraulic motor. Below, is the description of forward driving and reverse driving process of the hydraulic motors or wheel hubs.

- ✓ **4/3** Way Valve is presented.
- ✓ In Mid Position - Normal Position - Port ***A*** & ***B*** are Closed.

When Valve`s Piston moves to Left end position.

- ✓ Port ***A*** to Port ***T***
- ✓ Port ***B*** to Port ***P***
- ✓ Motor rotates Counter clockwise.

When Valve`s Piston moves to Right end position.

- ✓ Port ***A*** to Port ***P***
- ✓ Port ***B*** to Port ***T***
- ✓ Motor rotates clockwise.

As shown in figure 77,

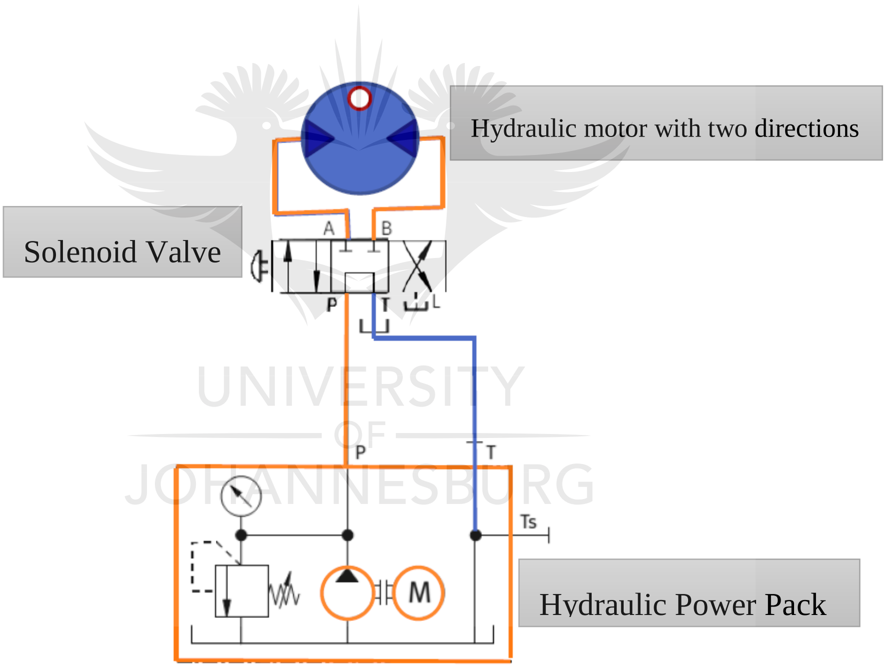


Figure 77 - Drive system circuit [39].

7.5.3. Adjustable Hydraulic Steering Cylinder Circuit Design & Functionality illustration.

The new design system will use a Double Acting Cylinder - Synchronous Cylinder as its steering mechanism. This cylinder has a piston rod on both sides. The piston rod is a through piston rod. Guidance of the piston rod is better as there are two bearing points. The force is identical in both directions of movement [63 - 65].

A) *Hydraulic Steering Cylinder Circuit System Design & Functionality Description*

The diagram consists of hydraulic power pack, 4/2 Way mono-stable Valve, flow control valve and hydraulic steering cylinder. Below, is the description of extraction and retractrion process of the lifting cylinders.

In normal position:

- ✓ Port ***P*** to Port ***T***
- ✓ Port ***A*** & Port ***B*** closed
- ✓ Cylinder in mid Position.

When actuated (steering to the right process):

- ✓ Port ***P*** to Port ***A***
- ✓ Port ***B*** to Port ***T***
- ✓ Cylinder moves to Extracted End Position.

When De actuated (steering to the left process):

- ✓ Back to normal position.
- ✓ Port ***A*** to Port ***T*** _ Depressurized on A side
- ✓ Port ***B*** to Port ***P*** _ Pressurized on B side
- ✓ Cylinder moves back to Retracted end Position.

As shown in figure 78 & 79.

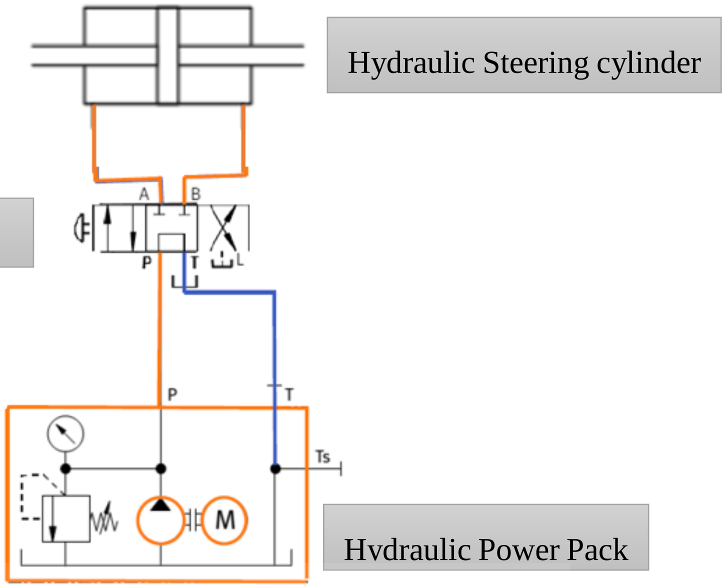


Figure 78 - Steering system circuit illustration [39].

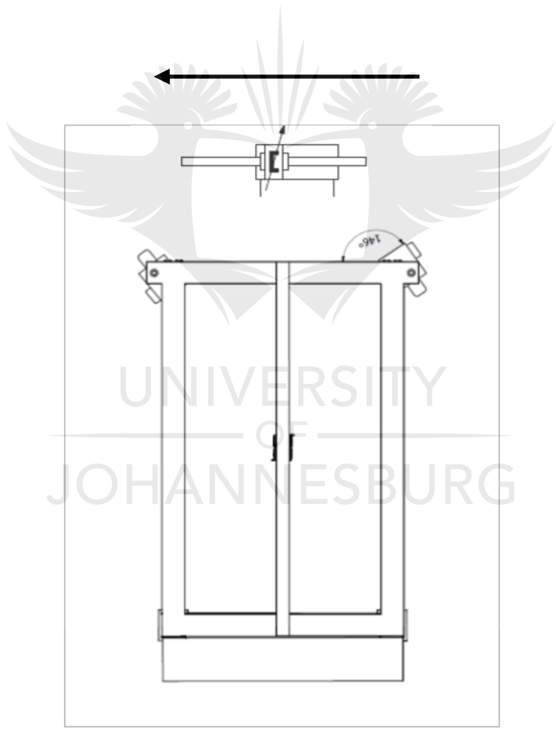


Figure 79 - Steering Illustration of Main Frame Structure - Top View

7.6. Hydraulic System Calculations for New System Design.

This section outline provides a summary of hydraulic cylinder and gear pump geometrics, force equations & calculations, detailed calculations are done in chapter 4, section 4.7.

7.6.1. Cylinder Force Calculations

Cylinder force can be obtained using equation 20 & 21.

$$F = P.\mathrm{A}.\mu_m \quad \text{..........} \quad (20)$$

$$A = \frac{\pi D^2}{4};\ A = \frac{F}{P \times \mu_m \times \pi} \quad \therefore D = \sqrt{\frac{4 \times F}{P \times \mu_m \times \pi}} \quad \text{..........} \quad (21)$$

where: $A = Area\ (m^2)$

$F = Force\ (N)$

$D = Diameter\ (m)$

$P = Pressure\ \ (Pa)$

$\mu_m = Mechanical\ efficiency$

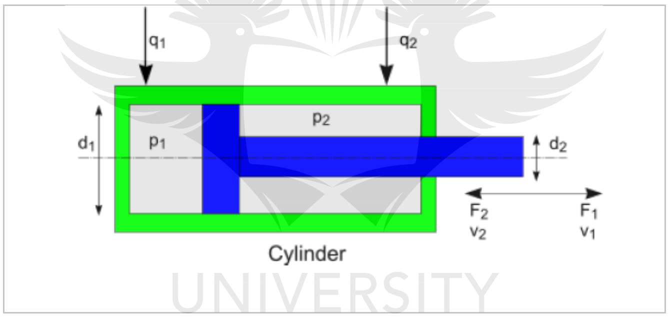


Figure 80 - Hydraulic Cylinder Schematic [39].

7.6.2. Hydraulic Wheel Hub Motor Pressure and flow Rate Calculation

Gear pumps are commonly used for pumping high viscosity fluids such as oil, paints, resins or foodstuffs. They are also preferred in applications where accurate dosing or high pressure output is required. Therefore, hydraulic wheel hubs for the drive system will be of gear pumps [44].

$$P = \frac{T}{V}\ \& \quad \text{..........} \quad (22)$$

$$Q = n \times V \quad \text{..........} \quad (23)$$

where: $P = Pressure\ (Pa)$

$T = Torque \quad (Nm)$

$V = Geometric\ Displacement\ Capacity\ (cm^3)$

$Q = Flow\ rate\ (l/min)$

$n = Speed \qquad (r/min)$

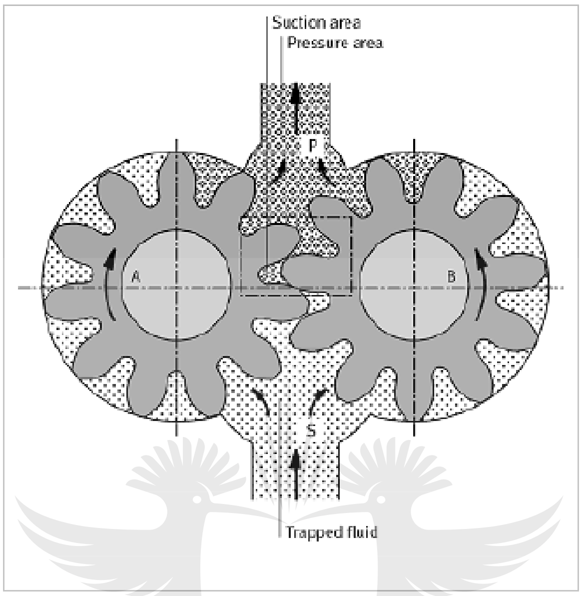


Figure 81 – External Gear Pump diagram [39].

7.6.3 Determining Hydraulic Wheel Hub Motor Power of the New Design System.

$P = \frac{2\pi NT}{60}$; $\omega = \frac{2\pi N}{60}$; $\omega = \frac{v}{r}$ .... (24)

Please note, $V_{max} = 5\frac{km}{hr}$ $(walking\ speed)$; $R_w = r = 0.541\ m$

$$\therefore \omega = {\frac{5}{3.6}}\Big/{0.541} = 3\ r/min$$

And $N = \frac{0.003\times 60}{2\pi} = 0.03\ rev/s$

Therefore; $P = \frac{2\pi \times 0.03 \times 149.1 \times 10^3}{60} = 468.411\ W,$

So each wheel will need $\boldsymbol{468.411\ W}$ in order to move the machine when loaded with its overall weight.

7.7. Solenoid Valve of the New System Design

A solenoid valve is an electrically controlled valve. The valve features a solenoid, which is an electric coil with a movable ferromagnetic core (plunger) in its center. In the rest position, the plunger closes off a small orifice. An electric current through the coil creates a magnetic field. The magnetic field exerts an upwards force on the plunger opening the orifice. This is the basic principle that is used to open and close solenoid valves [45].

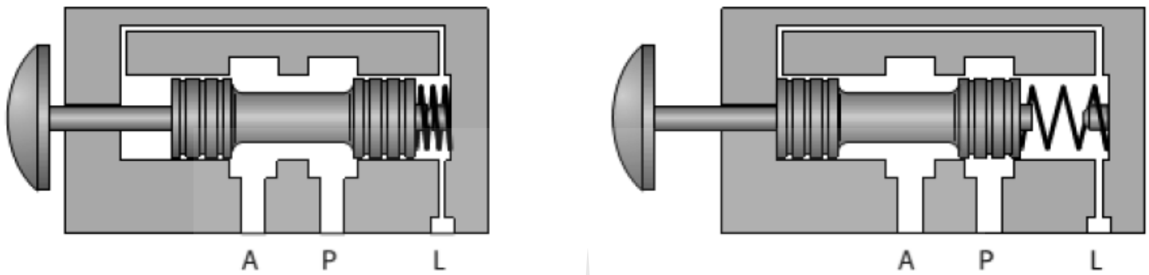


Figure 82 - Direction Control Valve Switching Positions [39].

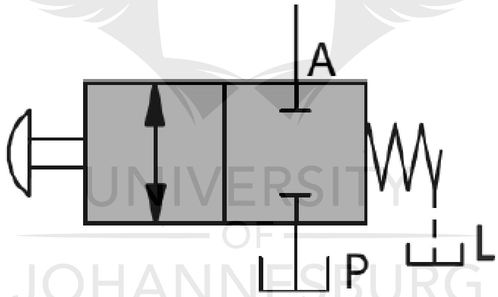


Figure 83 -Direction Control Valve Symbol [39].

CHAPTER EIGHT

DESIGN MODELLING OF ELECTRO-HYDRAULIC CIRCUITS FOR THE NEW DESIGN SYSTEM

8. Chapter Overview

The chapter outlines the design, description, and functionality of the Electro – Hydraulic systems of the new design. Suitable components Electro – Hydraulic systems are explained in detail in this chapter. Again, Electro – Hydraulic systems circuits are also populated and analysed to meet the requirements of the new design system and energy conversions in hydraulics are explained.

8.1. Electro- Hydraulics Background

Electro-hydraulic circuit consists of different components such as electric motor which converts electric energy into mechanical energy, the pump which converts mechanical energy into hydraulic energy and the actuator convert back hydraulic energy into mechanical energy. Control elements like valves are used which controls the fluid in the circuit such as direction control valves, flow control valves, solenoid valves & pressure relief valves, etc [39].

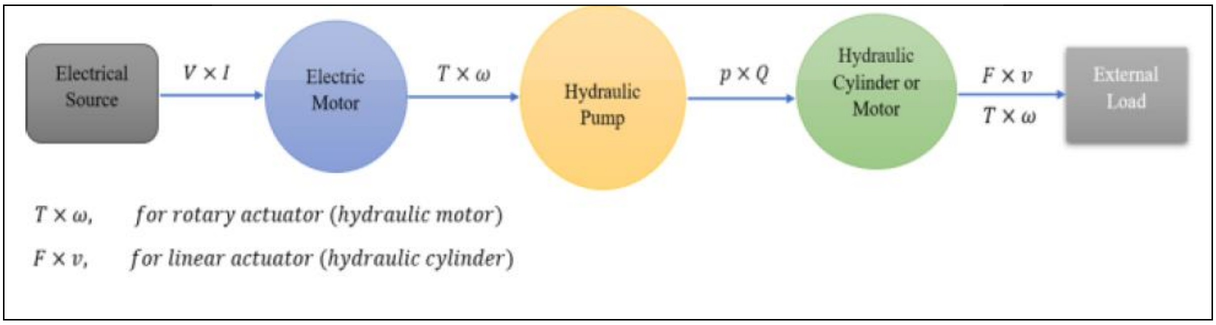


Figure 84 - Various energy conversions in hydraulics.

8.2. Background of Electro - Hydraulic Systems

Hydraulics involves the use of hydraulic fluids to perform mechanical work. Hydraulics are electro-controlled by an electrical source, thus voltage supply then signals are generated through 24V and sent to control valves for directional control of hydraulic fluid. Mechanical work is necessary to carry out movements and generate forces. The function of hydraulic drives is to convert the energy stored in hydraulic fluid into motion [39].

8.3. Description of Electrical Components of the New Design System

A relay is an electromagnetic switch operated by a relatively small electric current that can turn on or off a much larger electric current. The heart of a relay is an electromagnet (a coil of wire that becomes a temporary magnet when electricity flows through it) [39].

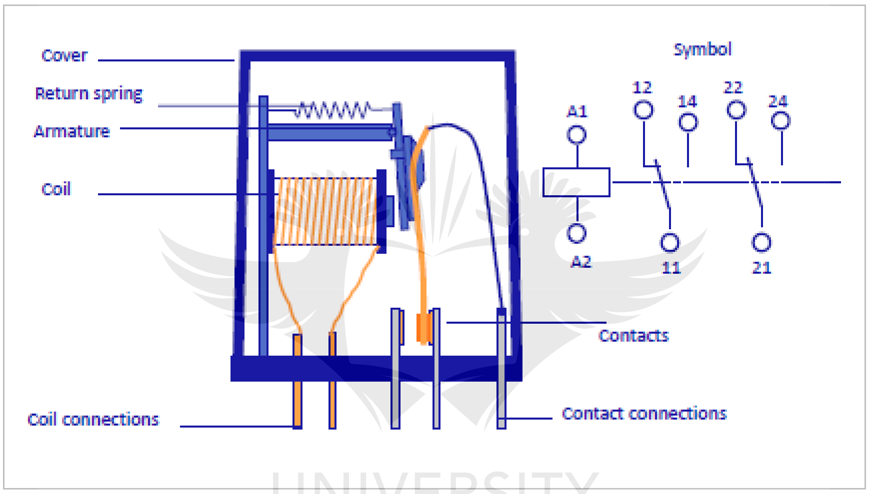


Figure 85 – Relay schematic [39]

The relay mainly consists of a coil and several independent contact sets, as shown in figure 85. Each contact set consists of a stationary contact and a movable contact. It also includes a stationary core and a movable core to confine the magnetic field. The movable contacts are coupled to the movable core. Therefore, when the coil is energized with the help of an additional electrical circuit, the movable core is pulled towards the stationary core, thus operating all its coupled contacts simultaneously. This movement either makes or breaks the connection of the movable contact with its respective fixed contact in each contact set [46].

8.3.1. Direct vs Indirect Relay Operation Illustration.

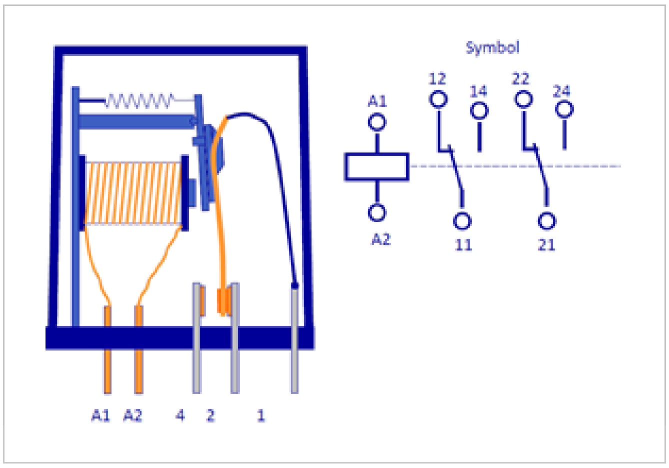


Figure 86 - Energized relay illustration with magnetic field (Normally opened) [39].

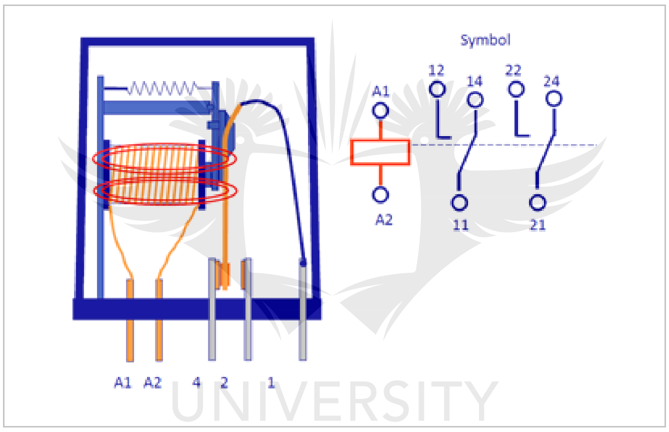


Figure 87 - Un-energized relay illustration_ no magnetic field (Normally opened) [39].

- The control circuit and main circuit operate with different voltages (such as 24 V and 230 V).
- The current through the coil of the directional control valve exceeds the permissible current for the pushbutton (such as where the current through the coil is 0.5 A and the permissible current through the pushbutton is 0.1 A).
- Several valves are operated with one pushbutton or one control switch [39].

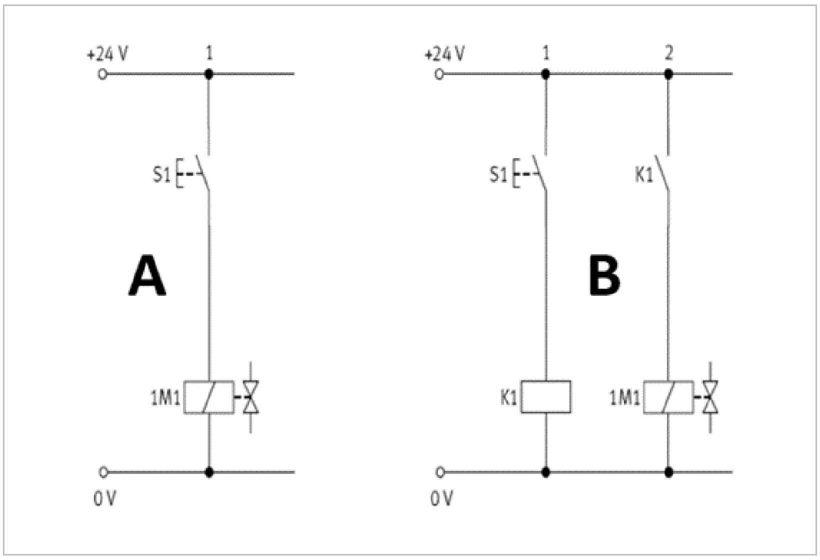


Figure 88 - A illustrates direct operation; B illustrates indirect operation of solenoid valve

8.3.2. Wiring Through Terminal

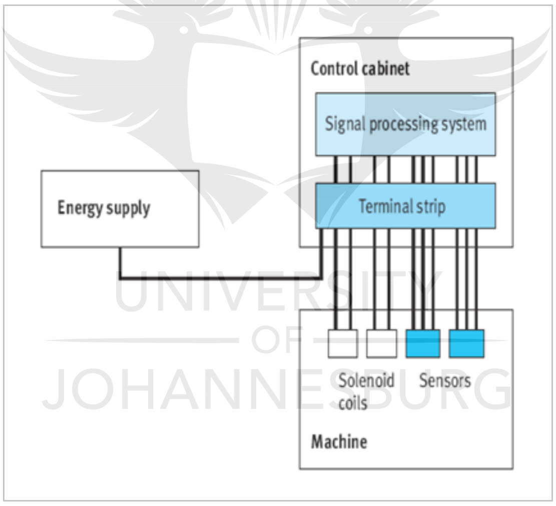


Figure 89 - Single terminal connection [39].

A) Why use Terminals:

- Cost effective setup (use of components that offer good optimization of the schematic diagram with respect to wiring complexity, use of components with a reduced number of connections).
- Easy fault finding (clear, easy to understand and precisely documented wiring). Quick repair.
- Quick repair (easy replacement of components by means of clamped or plug connections, no soldered-on components).

8.4. Testing and analysis of the Electro-hydraulic Circuit System Design

This section provides an outline of different operation of the electro-hydraulic circuit systems. Explanation of Direct control of a double-acting hydraulic cylinder and Indirect control of a double-acting hydraulic cylinder using a relay is carried out [65].

8.4.1. Lifting and Lowering of Load Circuit Illustration

a) The system consists of four double acting hydraulic lifting cylinders. Therefore, each hydraulic (linear) cylinder in four lifting cylinders will exert ¼ of 20-ton load capacity. Only one double acting hydraulic cylinder will be analyzed since all cylinders will be experiencing same force simultaneously when lifting and lowering loads.

b) Again, the new design system consists of two double acting cylinders to perform extraction and retraction enabling the system to be adjustable. Therefore, its retraction and extraction process are the same as for the lifting cylinders and they are explained below.

8.4.2. Relay-based Electro-Hydraulic Systems

In the electrical actuation of a hydraulic valve, the necessary actuating force is obtained electrically with the help of a solenoid. The off-centre core of the solenoid coil is pulled towards the center of the coil when the electric current is passed through it. This discrete movement of the core is used to actuate the solenoid valve. The solenoid valve in an electro-hydraulic system acts as an interface between the hydraulic part and the electrical part of the system [46].

8.4.3. Indirect and Direct Control of a Double-acting Hydraulic Cylinder using a Relay.

In the electrical actuation of a hydraulic valve, the necessary actuating force is obtained electrically with the help of a solenoid. The off-centre core of the solenoid coil is pulled towards the centre of the coil when the electric current is passed through it. This discrete movement of the core is used to actuate the solenoid valve. The solenoid valve in an electro-hydraulic system acts as an interface between the hydraulic part and the electrical part of the system [46].

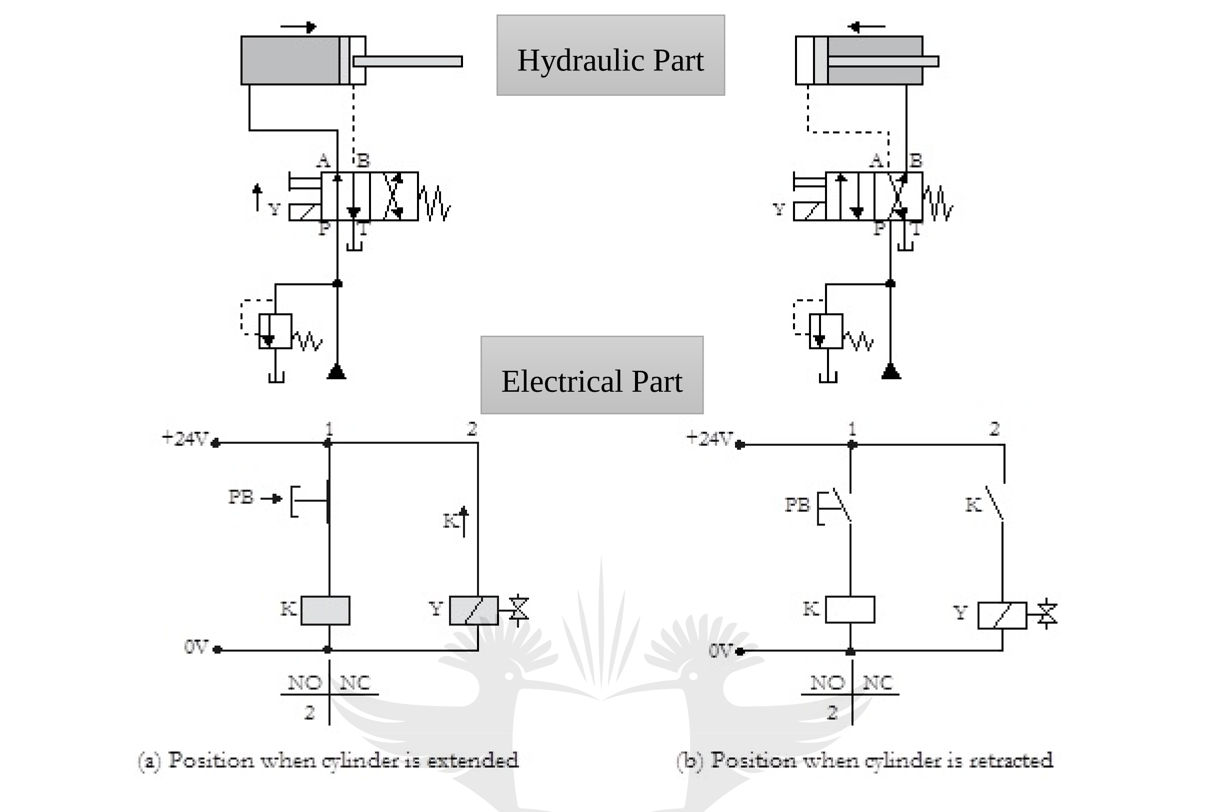


Figure 90 - Indirect control of a double-acting hydraulic cylinder using a relay [46].

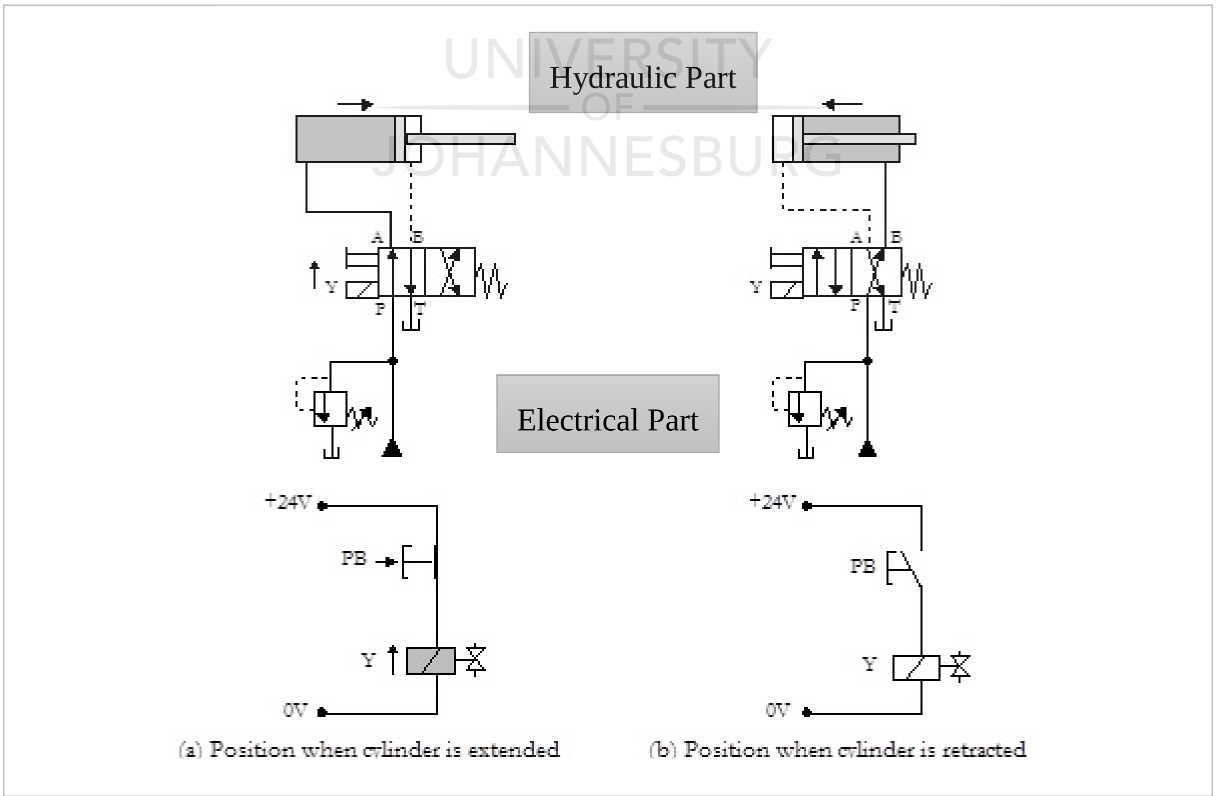


Figure 91 - Direct control of a double-acting hydraulic cylinder [46].

A) Solenoid Valve Functionality

In the normal position of the solenoid valve, the pressure port P is connected to the working port B, and the working port A is connected to the tank port T. The valve is actuated when the rated voltage is applied to the coil Y. In the actuated position of the valve, the port P is connected to the port A, and the port B is connected to the port T. When supply to the coil is cut off, the valve returns to its normal position. This valve can be used as the final control element for controlling a double-acting cylinder [64, 65].

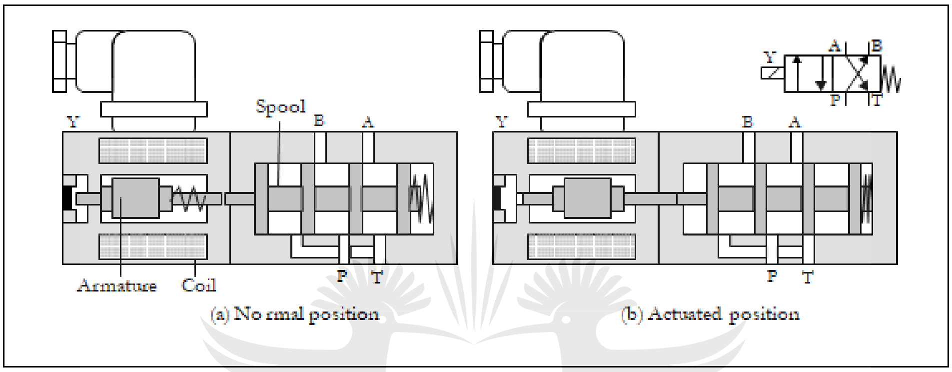


Figure 92 - 4/2-way Single-solenoid Valve, Spring Return

8.5. Electric Hydraulic Circuit Components for Figure 89 & 90 Include

This section provides detailed descriptions of electro-hydraulic circuits shown in figure 90 & 91.

8.5.1. Logic Controls, Electric

Logic controls are used to start or stop various operations in hydraulic systems based on the satisfaction of certain conditions in these systems. Two of the most important logic functions are ‘AND’ and ‘OR’ [46].

8.5.2. Memory Function

A circuit/device with a memory function ‘remembers’ its last output state even after the input signal from an input device responsible for this output has been removed [46].

8.5.3. Electromagnetic Relay

The relay mainly consists of a coil and several independent contact sets. Each contact set consists of a stationary contact and a movable contact [46].

8.5.4. Pushbutton Station

A pair of successive two-digit numbers is used to designate the terminals of a contact in the pushbutton station. In the two-digit number, the digits in the unit place indicates the function of the contact (that is, whether it is a NO type or an NC type) [46].

8.5.5. Push-button Switch

A push-button switch is a device used to close or open an electric circuit [46].

8.5.6. Control Devices

Several control elements such as pushbuttons, relays, timers, and sensors are used in electro-hydraulic systems to realize various control functions [46].

8.6. Terminal Markings of Contacts is Important

For identification purpose, the terminals of each of the contacts of the control device are designated with a set of numbers based on the function of the contact and the type of control device [46].

8.7. Output Feedback Controller Design of Hydraulic Actuator Systems

The new system design consists of a hydraulic unit, a 486/66- based PLC equipped with a Metrabyte M5312 quadrature incremental encoder card and a DAS-16 analog/digital (AID) conversion card and, an external force source facility (as shown in figure 90 & 91). The pump provides constant operational supply pressure up to 300 MPa. The hydraulic valve is a low-cost closed-center four-way proportional valve. The positioning of the valve spool is based on the pulse width modulation principle. Load is used as an environment [47].

Three pressure transmitters read the pump, supply line, and return line pressures with ±l% accuracy. An incremental encoder with sensing resolution of 0.06 mm reads the displacement of the cylinder piston. The control signal generated by the control algorithm is converted to an analog signal by the AID card and is transmitted to the hydraulic valve amplifier, as shown in figure 93 & 94 [66, 67]. The valve operates within the range ± 1.8 volt and has a dead band of $\approx \pm 0.15$ volt within which the actuator does not move. The reaction time of the valve from the neutral position to maximum spool travel is 120 ms [47].

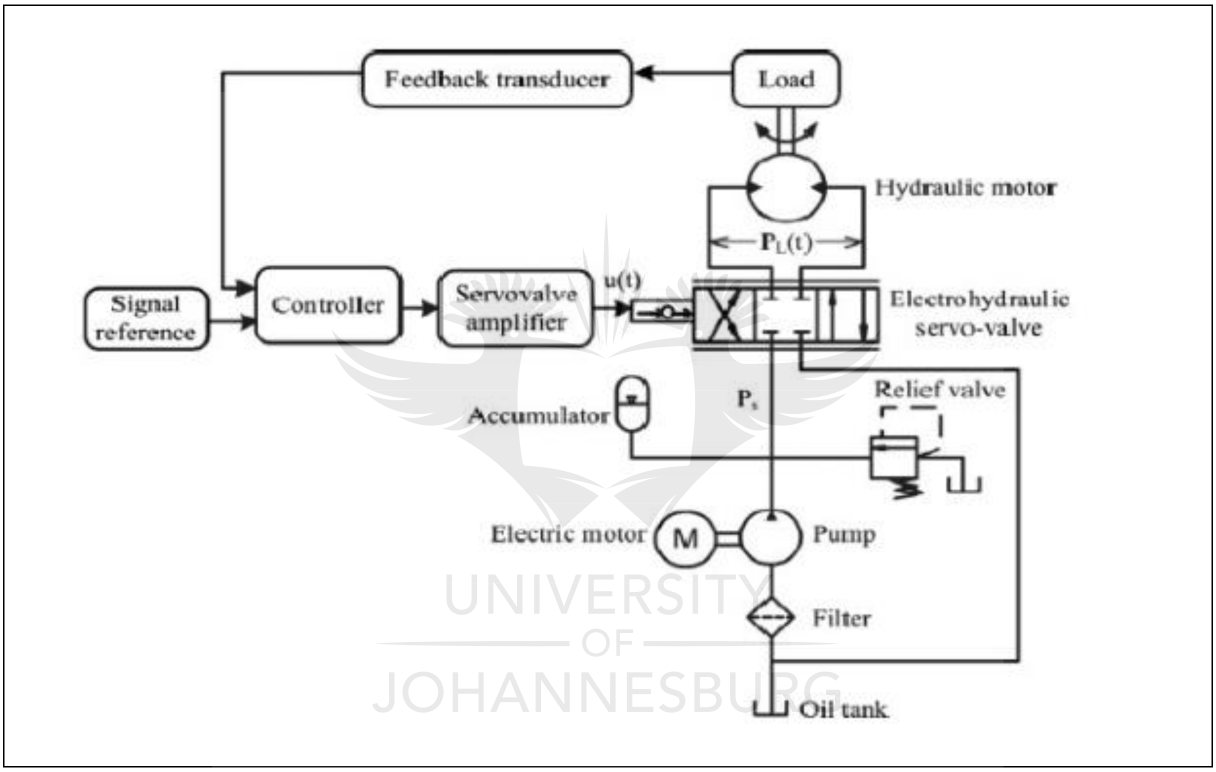


Figure 93 - Output feedback controller design of hydraulic actuator systems [48].

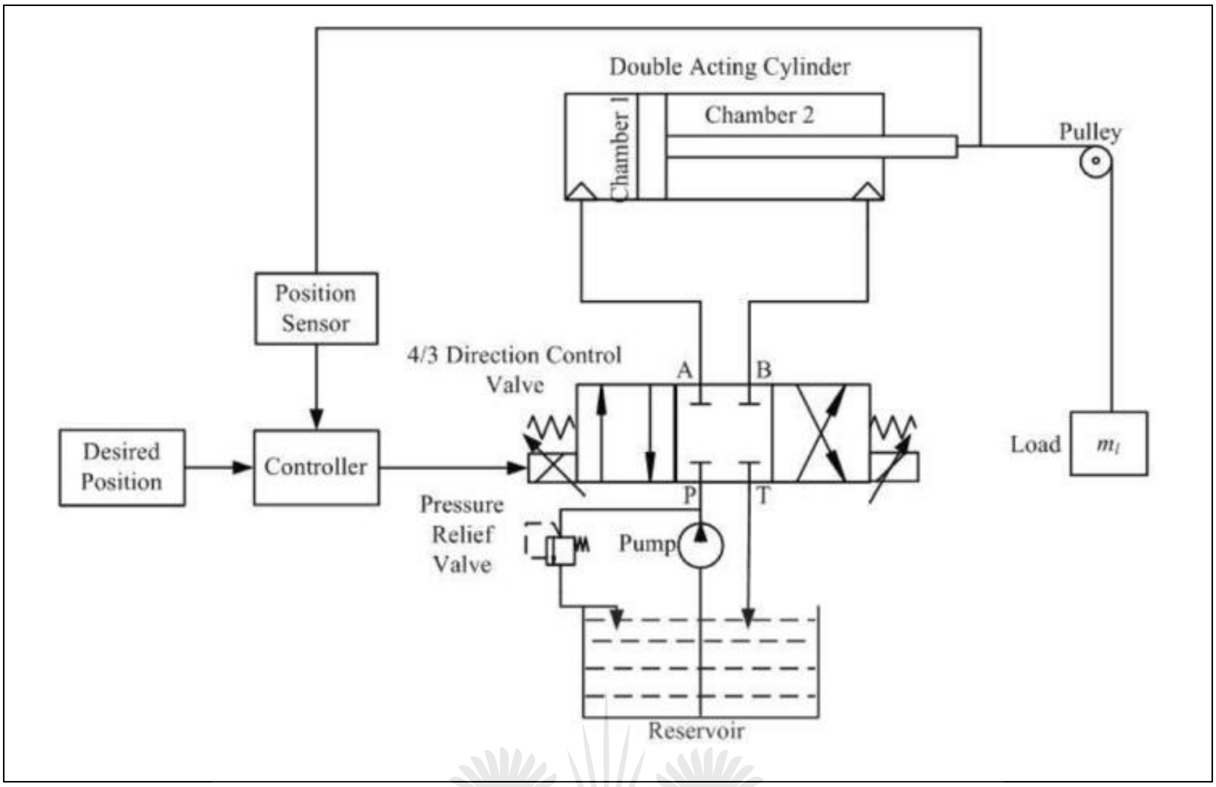


Figure 94 - Output feedback control of electro-hydraulic system [49].

CHAPTER NINE

CONCLUSION AND DISCUSSION

9. Chapter Overview

The chapter outlines the discussion, recommendations, and conclusion of the new design system research. Suitable materials for construction of the new design system are explained in detail and verified. Simulation of the new design system's components were conducted to validate the machine parts. Electro-hydraulic circuit design and components selection was also done. Therefore, in this section, discussions and conclusion will be populated using the above-mentioned research information. Appropriate method for designing the new system design is has been tested and chosen to provide better solution to the MHS manufactures and/ industries on how to design an efficient, effective, economical and safe to operate MHS while saving time and costs of the company.

9.1. Discussion of the Research

This section provides an overview of the research's components material selection and results summary of stress analysis simulations.

9.1.1. Split Joint Shaft Simulation Discussion

Material chosen for manufacturing of the split joint shaft and technical design modelling of the component in terms of shape and dimensions is valid as it has been verified through Autodesk Inventor's Stress Analysis. According to the component's physical properties, yield strength is 207 MP and the maximum Von Mises stress induced by the component is 5.513 MPa giving a safety factor of 15 ul, (as shown in table 38 & 40), as it experiences point load reaction stress. It has been observed from result summary table, (as shown in table 39), that the maximum deflection is 0.000141 mm under steering effort load. It can be concluded that the designed steering clamp bracket is reliable and that its operational' life span will last, (as shown in table 41, Factor of Safety related to Stress).

9.1.2. Rear and Front Swivel Support Bracket Simulation Discussion

Material chosen for manufacturing of front swivel & rear support bracket and technical design modelling of the component in terms of shape and dimensions is valid as it has been verified through Autodesk Stress Analysis. According to the component's physical properties, yield strength is 760 MP and the maximum Von Mises stress induced by the component is 755.754 MPa giving a safety factor of 1.5, (as shown in table 37) as it experiences bending moment stress. Support brackets is formed by means of fabrication of 40 mm steel plates to form a strong reinforced supportive structure hence it has been observed from result summary table, (as shown in table 37), that the maximum deflection is 0.004981 mm under remote point load. It can be concluded that the designed Rear and Front Swivel Support Bracket is reliable and that its operational' life span will last, (as shown in table 41, Factor of Safety related to Stress) [63 - 65].

9.1.3. Steering Clamp Bracket Simulation Discussion

Material chosen for manufacturing of the steering clamp bracket and technical design modelling of the component in terms of shape and dimensions is valid as it has been verified through Autodesk Stress Analysis. According to the component's physical properties, yield strength is 207 MP and the maximum Von Mises stress induced by the component is 23.26 MPa giving a safety factor of 8.899ul, as shown in table 31 & 33, as it experiences bending moment stress. It has been observed from result summary table, as shown in table 33, that the maximum deflection is 0.3165 mm under steering effort load. It can be concluded that the designed steering clamp bracket is reliable and that its operational' life span will last almost forever, (as shown in table 40, Factor of Safety related to Stress).

9.1.4. Spreader Beam Simulation Discussion

Material chosen for manufacturing of the spreader beam and technical design modelling of the component in terms of shape and dimensions is valid as it has been verified through Autodesk Stress Analysis. According to the component's physical properties, yield strength is 760 MPa (as shown in 5.3) and the maximum Von Mises stress induced by the component is 199.587 MPa giving a safety factor of 3.81 ul, as shown in table 30, as it experiences remote point load reaction stress. It has been observed from result summary table, as shown in table 30, that the maximum deflection is 2.709 mm under remote point loads. It can be concluded that the designed spreader beam is reliable and that its operational' life span will last (as shown in table 41, Factor of Safety related to Stress).

9.1.5. Main Frame Structure Simulation Discussion

The main frame structure' material selection and design are valid as they have been verified through Autodesk Inventor Stress Analysis as 20-ton load simulation gives 5.325 mm deflection, and it falls within <10 mm range, as shown in table 26 & figure 53. According to the component's physical properties, yield strength is 760 MPa (as shown in 5.3) and the maximum Von Mises stress induced by the component is 174.125 MPa giving a safety factor of 4.36 ul, as it experiences remote point load reaction. Therefore, the system is safe to operate 20-ton load capacity.

9.2. Conclusion

In conlusion, the main objective of this research has been achieved through the design and development of the new proposed MHS that is capable of replacing the use of very big forklift trucks within indoor manufacturing companies. Large forklift trucks rely on ICE power source which unfortunately poses health risks to workers. ICE produces exhaust fumes (CO) while running. Exhaust fumes are harmful to human health [63 - 65].

Therefore, the research beacame a success whereby a new proposed MHS has been designed using Autodesk Inventor Professional and material selection of the new design system's components has been carried out and verified in relation with their strength & reliability properties. Through this paper and its engineering analysis, it is proven that the use of internal combustion engines in heavy duty handling systems that are operated within indoor manufactring factories and or internal logistics can be eliminated and replaced with an eco-friendly hydraulic systems technology. Therefore, this new system design promotes Occupational Health and Safety of people working in industrial areas where Bulk Material Handling systems are in place.

The new system was designed and it consist of four double-acting hydraulic cylinders interconnected with spreader beam responsible for lifting and lowering, as well as two double-acting hydraulic cylinders that will expand the system making it adjustable, a hydraulic steering cylinder for steering & turning the wheels and four hydraulic motors that will drive the system from point A to point B. Electric hydraulic components selection for new design system has been conducted.

Vehicle dynamics of the new proposed system were modelled, tested, and verified. The overall system's TE was calculated to discover the power required for the hydraulic wheel hub motor' to move the new proposed system under 20-ton load. When the new design system is under 20-ton load, TE was found to be 250.623 kN, hydraulic wheel hub motor torque was 149.1 kN.m and power required to overcome TE was 468.411 W, on each wheel.

Hydraulic power pack system of the new design system was developed and verified accordingly using thermo fluids laws and principles. Pump power required to supply the hydraulic system of the new design was found to be 1458.33 W and the pump motor power was 2525.9 W. Hydraulic pipe tubing of the new design system was also calculated and the pipe's inside diameter was found to be 25 mm. Steering system modelling of the new design has been carried out. Under load, it has been found that the steering cylinder produces a steering effort of 278.49

kN, thus making the steering clamp bracket and the split joint shaft experiences steering bending moment of 128.1 kN.m at maximum turning angle of 94.13°.

The simulation and technical modelling of the new system design through engineering calculations shows that the new design can handle 20-ton load capacity. Results summary very minimal deflection and Von Mises stress values. The systems induce a deflection of 5.325 mm and Von Mises stress of 174.125 MPa giving a safety factor of 4.36 ul under full load capacity.

Electro-hydraulic circuit systems were designed and developed for the new proposed design system. The functionality of the controls system of the new design was also described. Through the development of the electro-hydraulic circuits and control systems, it can be concluded that the new design system was based on Industry 4.0 principles.

9.3. Impact of the New Proposed System on Society and Benefits

The Automated Handling System will be used, both outdoor and indoor. The system must comply with safety standards to ensure that it does not endanger personnel's operating the machine. The lifting mechanism will be designed so to be acceptable to the user and must meet the user's needs. The machine will have a positive impact in the society; hence some personnel will be trained and supervisor to operate the lifting machine. Manufacturing the equipment locally, will contribute to skills development in South Africa and add value to the manufacturing sector.

9.3.1. Benefits

a) Materials handling management is among many factors that contribute to improve a company's performance.

Materials handling makes production flow possible, as it gives dynamism to static elements such as materials, products, equipment, layout, and human resources.

9.4. New System Design Recommendations

9.4.1. Conditions of lifting Machines

The new Automated handling system will comply with the requirements as set out in the legislation and standards.

- Performance testing and inspection must be carried out in terms of regulations
- Load test certifications for the mobile lifting machine will be in place.
- Effective inspection programmes must be complied with.
- Notices required for the machine will be in place including, warning signs, no unauthorised use.
- If the machine is found to be of, substandard condition should be removed from service immediately

9.4.2. Training is mandatory

All operators and assistants of the lifting machine must be trained and declared competent to operate the machine. Lifting equipment operator must receive training and recertification every two years.

9.4.3. Personal Protective Equipment (PPE)

By law it is required that when at the working environment, protective clothing or gear must be wear at all time. This ensure both the safety of person operating the machine and the safety of the machine.

Lifting equipment operators should always wear prescribed PPE, such as:

1. Safety boots
2. Hearing protection is to be used in noisy areas
3. Hand gloves
4. Safety glasses
5. And preferable working suite

The PPE sign will be presented on the working space.

9.4.4. Warning signs

Generally, the best safety measure is precaution, which entails the appropriate training and understanding of test equipment to be used. Extreme care must be taken to avoid moving weights, which can potentially inflict great injury or damage.

9.4.5. Ergonomics

Ergonomics (or human factors) is the study of efficiency in the workplace. It is concerned with the interaction between humans and other elements. The aim of ergonomics' in this design to find the best fit between the equipment and the operators. The equipment must be used as

- The operator must be familiar with the equipment and the surrounding environment
- The operator must be aware of the safety regulations and must be familiar with user manual.
- Always ensure that when operating the equipment, maintain an upright position.
- Quick movement must be avoided when equipment is carrying the load.

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Appendices

Appendix A

Engineering Regulations & OHS standards and Codes

1. Section 27 of the Engineering Profession Act, 2000 (ECSA)

This act empowers the Council to draw up codes of practice in addition to codes of conduct and requires all registered persons to comply with such codes. Failure to do so constitutes improper conduct and will be dealt with the Council as such. The engineering work identified for the professional categories of registration in the proposed draft regulations is generic in nature. It does not identify engineering disciplines and sub-disciplines. Reliance is placed on codes of conduct and codes of practice to determine work within the identified work, such professionals may undertake that is commensurate with their education, training, experience, and contextual knowledge.

2. Occupational Health and Safety act 85 of 1993 (OHS act)

To provide for the health and safety of persons at work and for the health and safety of persons in connection with the use of plant and machinery; the protection of persons other than persons at work against hazards to health and safety arising out of or in connection with the activities of persons at work; to establish an advisory council for occupational health and safety; and to provide for matters connected therewith.

3. Driven Machinery Regulations, 2015

The Driven Machinery Regulations were published on 24 June 2015 in Government Gazette No.38905 with the aim of protecting employees against the dangers associated with the use of Driven Machinery. The aim of these guidance notes is to explain in simple language the provisions of the Driven Machinery Regulations and to stress the principle of self-regulation.

4. **South African Bureau of Standards (SABS)**

SABS is a leading business services provider to organizations worldwide, offering a range of services for management system certification, product testing and certification, and standardization.

SABS provide standards that enhance the competitiveness of South Africa, and which are the basis for consumer protection, health, safety, and environmental issues.

5. **International Organization for Standardization (ISO)**

ISO is an international standard-setting body composed of representatives from various national standards organizations.

Appendix B

Structural Steel Catalogue

1. **Square Tubing (Hot Rolled),** data table

Square Tubing (Hot Rolled) M

Dimensions	1.6mm	2mm	2.5mm	3mm	3.5mm	4mm	4.5mm	5mm	6mm	8mm	10mm
12.7 x 12.7	0.575										
15.8 x 15.8	0.731	0.894									
19.0 x 19.0	0.889	1.092									
25.0 x 25.0	1.200	1.480	1.819	2.146							
32.0 x 32.0	1.529	1.892	2.334	2.764							
38.0 x 38.0	1.847	2.289	2.830	3.359	3.876	4.380					
40.0 x 40.0	1.943	2.408	2.980	3.539	4.085	4.620					
50.0 x 50.0	2.442	3.033	3.761	4.476	5.179	5.869	6.548				
60.0 x 60.0	2.944	3.660	4.544	5.416	6.275	7.122	7.957	8.779	10.387		
63.0 x 63.0	3.094	3.847	4.778	5.697	6.603	7.497	8.379				
75.0 x 75.0	3.685	4.587	5.703	6.807	7.898	8.977	10.043	11.098	13.169		
100.0 x 100.0		6.165	7.676	9.174	10.660	12.133	13.595	15.044	17.904		
120.0 x 120.0				11.053	12.852	14.639	16.413	18.176	21.663		
150.0 x 150.0				13.835	16.098	18.348	20.586	22.812	27.226	35.907	44.391
175.0 x 175.0					18.610	21.219	23.816		31.532	41.648	51.567
200.0 x 200.0							27.215		35.822	46.505	56.965
220.0 x 220.0									39.523	52.302	64.884
250.0 x 250.0									45.242	59.065	72.665
285.0 x 285.0									51.730	68.579	85.230

2. **Universal Beams, Parallel H Section,** data table

Universal Columns SANS 50025 / EN 10025 Grade S355JR

	KG/M	Web Dimensions	Flange Dimension	Height	Width
152 x 152	23.000	6.100	6.800	152.400	152.400
152 x 152	30.000	6.600	9.400	157.400	152.900
152 x 152	37.000	8.100	11.500	161.800	154.400
203 x 203	46.100	7.300	11.000	203.200	203.200
203 x 203	52.000	8.000	12.500	206.200	203.900
203 x 203	60.000	9.300	14.200	209.600	205.200
203 x 203	71.000	10.300	17.300	215.900	206.200
203 x 203	86.100	13.000	20.500	222.300	208.800
254 x 254	73.100	8.600	14.200	254.200	254.000
254 x 254	88.900	10.500	17.300	260.400	255.900
254 x 254	107.100	13.000	20.500	266.000	258.000
254 x 254	132.000	15.600	25.100	276.400	261.000
254 x 254	167.000	19.200	31.700	289.100	264.500
305 x 305	96.900	9.900	15.400	307.800	304.800
305 x 305	117.900	11.900	18.700	314.500	306.800
305 x 305	136.900	13.800	21.700	320.500	308.700
305 x 305	158.100	15.700	25.000	327.200	310.600
305 x 305*	198.100	19.100	31.400	339.900	314.500

3. **Plates (Commercial Quality, S355 JR / JO and Vastrap Plates)**, data table.

Wearplate 200 (W200) - SS10/200 [HARD WEARING PLATE (BENNOX)]

Dimensions	5mm	6mm	8mm	10mm	12mm	16mm	20mm	25mm	32mm	35mm	40mm	45mm	50mm
2500 x 1200	117.750*	141.300	188.400	235.500	282.600	376.800	471.000	588.750	753.600	824.250*	942.000*	1059.750*	1177.500*
4000 x 2000	314.000*	376.800	502.400	628.000	753.600	1004.800	1256.000	1570.000	2009.600		2512.000*		3140.000*

4. Universal Columns I-Section

Universal Beams SANS 50025 / EN 10025 S355JR

	KG/M	Web Dimensions	Flange Dimension	Height	Width
203 x 133	25.100	5.800	7.800	203.200	133.400
203 x 133	30.000	6.300	9.600	206.800	133.800
254 x 146	31.100	6.100	8.600	251.500	146.100
254 x 146	37.000	6.400	10.900	256.000	146.400
254 x 146	43.000	7.300	12.700	259.600	147.300
305 x 102	24.800	5.800	6.800	304.800	101.600
305 x 102	28.200	6.100	8.900	308.900	101.900
305 x 102	32.800	6.600	10.800	312.700	102.400
305 x 165	40.300	6.100	10.200	303.800	165.100
305 x 165	46.100	6.700	11.800	307.100	165.700
305 x 165	54.000	7.700	13.700	310.900	166.800
356 x 171	45.000	6.900	9.700	352.000	171.000
356 x 171	51.000	7.300	11.500	355.600	171.500
356 x 171	57.000	8.000	13.000	358.600	172.100
356 x 171	67.100	9.100	15.700	364.000	173.200
406 x 140	39.000	6.300	8.600	397.300	141.800
406 x 140	46.000	6.900	11.200	402.300	142.400
406 x 178	54.100	7.600	10.900	402.600	177.600
406 x 178	60.100	7.800	12.800	406.400	177.800
406 x 178	67.100	8.800	14.300	409.400	178.800
406 x 178	74.200	9.700	16.000	412.800	179.700
457 x 191	67.100	8.500	12.700	453.600	189.900
457 x 191	74.300	9.100	14.500	457.200	190.500
457 x 191	82.000	9.900	16.000	460.200	191.300
457 x 191	89.300	10.600	17.700	463.600	192.000
457 x 191	98.300	11.400	19.600	467.600	192.800
533 x 210	82.200	9.600	13.200	528.300	208.700
533 x 210	92.100	10.200	15.600	522.100	209.300
533 x 210	101.000	10.900	17.400	536.700	210.100
533 x 210	109.000	11.600	18.800	539.500	210.700
533 x 210	122.000	12.800	21.300	544.600	211.900

5. Round Bar SANS 50025 / EN 10025 S355JR

Round Bar SANS 50025 / EN 10025 S355JR

Dimensions	45mm	50mm	55mm	60mm	65mm	70mm	80mm	90mm	103mm
	12.485	15.413	18.650	22.195	26.049	30.210	39.458	49.940	65.408

Appendix C

Engineering technical equations

1. **Turning Radius**

$TR = D + (MOL - TRR)$ [m].. (2)

2. **Bending Moment**

$BM = P \times d$ [N.m]…………………………………………………………………….. (4)

3. **Friction Force**

$F = \mu(m.g)$ [N]…………………………………………………………………….. (5)

4. **Rolling Resistance**

RR[N] = W_GV (N)+μ [N]……………………..………………………………………. (7)

5. **Total Tractive Effort**

TTE[N]=RR [N]+Fa[N] ………………………………………………………………… (6)

6. **Hydraulic Wheel Motor Torque**

$T_w = TTE \times R_w \times R_f$ [N.m] ……………………………………………………………… (9)

7. **Bending Stress**

$\sigma = \frac{BM}{I_x}$ [MPa]……………………………………………………………………… (3)

8. **Shear stress**

$\tau_B = \frac{VA\bar{y}}{Ib}$ [MPa]...………………………………………………………………… (10)

9. Total steering angle

$$[\cot\theta - \cot\varphi = \frac{c}{b}] \quad + [R = \frac{b}{\sin\theta} + \frac{a-c}{2}] \text{ [degrees]} \dots\dots (13)$$

10. Pump Power Capacity

$$P = \frac{P_p + Q_n}{61.2 \times \mu_v} \text{ [KW]} \dots\dots (16)$$

11. Wall Thickness of the Pipe Tubing

$$\delta = \frac{Pd}{2\,[\sigma]} \text{ [m]} \dots\dots (17)$$

12. Factor of safety

$$Factor\ of\ \ Safety = \frac{yield\ stress}{working\ stress} \dots\dots (19)$$

13. Cylinder Force

$$F = P.\text{A}.\mu_m \text{ [N]} \dots\dots (20)$$

14. Gear Pump power

$$P = \frac{T}{V} \text{ [KW]} \dots\dots (21)$$

15. Flow rate

$$Q = n \times V \text{ [l/s]} \dots\dots (23)$$

16. Mechanical Power

$$P = \frac{2\pi NT}{60} \text{ [KW]} \dots\dots (24)$$